Valuing climate change effects upon UK agricultural GHG emissions:

Spatial analysis of a regulating ecosystem service

Dave Abson[1*], Mette Termansen[2], Unai Pascual[3,4,5], Uzma Aslam[1], Carlo Fezzi[6]and Ian Bateman[6]

[1] School of Earth and Environment, University of Leeds, LS2 9JT, UK.
[2] Department of Environmental Science, Frederiksborgvej 399, 4000 Roskilde, Aarhus, University, Denmark.
[3] Department of Land Economy, University of Cambridge, CB39EP, Cambridge, UK
[4] Basque Centre for Climate Change (BC3), Alameda Urquijo, 4-4, 48008, Bilbao, Basque Country.
[5] Ikerbasque Basque Foundation for Science. Alameda Urquijo, 36-5, 48011 Bilbao, Basque Country
[6] Centre for Social and Economic Research on the Global Environment (CSERGE), School of Environmental Sciences, University of East Anglia, Norwich, NR4 7TJ, UK

Abstract

This article provides estimates of the physical and economic value of changes in greenhouse gas (GHG) emissions projected to arise from climate change induced shifts in UK agricultural land use during the period 2004-2060. In physical terms, significant regional differences are predicted with the intensity of agricultural GHG emissions increasing in the upland north and western parts of the UK and decreasing in the lowland south and east of the country. Overall these imply relative modest increases in the physical quantity of emissions. However, rapid rises in the expected marginal value of such emissions translate these trends into major increases in their economic value over the period considered.

Keywords: Climate change, GHG emissions, ecosystem services, land use change, agriculture.

---

[*] Corresponding author email: d.abson@see.leeds.ac.uk

This paper has not been submitted elsewhere in identical or similar form, nor will it be during the first three months after its submission to the Publisher.

Introduction

Roughly 77% of UK land is under agricultural production (Defra, 2007), with its primary purpose being the provision of food and fibre. However, the conversion and management of land for such provisioning purposes typically also impacts upon the provision of other ecosystem services. One of the major impacts of agricultural land management and conversion is upon the ability of the land to contribute to climate regulation through the accumulation of atmospheric CO_2 as carbon in biomass and soil organic carbon (SOC). Agricultural land uses differ both in their capacity to store carbon and in the direct and indirect emissions of greenhouse gases (GHGs) associated with the management of those land uses. Agriculture accounts for approximately 9% of the UK's net greenhouse gas (GHG) emissions[1](Thomas et al. 2011); a figure which is near to the average for the EU-15 nations (EEA, 2005).

The impacts of land use change on agricultural GHG emissions has received considerable attention (e.g. Hediger 2006; Moran et al. 2011; West et al. 2003). However, despite the inherent spatial variability of agriculture, to date there has been a lack of fine resolution, spatially explicit analyses of land use changes and associated GHG emissions. This is problematic because, as numerous commentators have noted (see, for example, Dale 1997; Marland et al. 2003; Rounsevell et al. 2009; as well as Fezzi et al, 2012, in this volume), alongside the effects of policy and markets, agricultural land use varies according to both cross sectional variations in the physical environment and temporal variations in those characteristics; of which the most rapidly evolving is climate change. Given that per hectare GHG emissions vary according to land use type (Lal 2004), changes in land use will result in variations in agricultural GHG emissions (Foley et al. 2005; Smith 2004).

Agriculture contributes to GHG emissions via a plethora of pathways including the use of fossil fuel in farm machinery, direct nitrous oxide emissions from fertilizer application (as well as indirectly emissions from the energy used in their production), methane emissions from livestock and emissions from the tillage of soils (Lal 2004; Pretty et al. 2001; Smith et al. 2008). Land use change can also result in the release or accumulation of stored soil organic carbon (SOC) depending on the soil disturbance regime of a given land use. Land use change also alters stocks of carbon stored in the above and below ground biomass of a given agricultural land use (Erb 2004). For example, root crops have a higher stock of carbon in biomass than permanent grasslands (Cruickshank et al. 1998). Given that both predicted climate change patterns and the productivity of agricultural land varies across regions, alterations in the agricultural output mix would be expected to vary across space and have varying impacts across space in terms of GHG emissions, even at relatively fine spatial scales. Therefore, models of future GHG emissions in agriculture should ideally be spatially explicit, account for fine resolution adjustment to

---

[1] Reference to greenhouse gas (GHG) emissions is often made in termsof carbon (or tonnes of carbon) 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. Additionally, the term unit cost or price of CO_2e, is used interchangeably for the notion of the marginal value of a reduction of a tonne of CO_2e whether it is transacted in the market or not.

climate change through changes in land use and consider the impact that those land use changes will have on GHG emissions[2].

Economic assessment of variations in the GHG regulatory services arising from agricultural change relies on estimates of the value of carbon emissions or mitigation. A vibrant literature has provided a framework for such analysis (e.g., Downing et al. 2005; Dasgupta; 2006, Ekins 2007; Stern, 2007; Nordhaus, 2008). This notes that for scenario analyses future carbon prices are dependent on the assumed emission trajectory, abatement technology, discount rates and the adopted climate projections (DECC 2009a). As such, future carbon prices are endogenous to the emission and climate scenarios upon which they are based.

A recent study by McLeod et al (2010) estimates GHG abatement costs from UK agriculture based on changes in management and farm practices. Here instead of analysing the abatement potential through management changes, we build upon the emerging literature examining the incorporation of farmer decision-making in regional climate impact modelling (e.g., Risbey et al. 1999, Seo et al. 2008). The approach taken here is to predict the effect of climate change on farmers' decisions over land use change and its subsequent impact on carbon regulating services. We use the structural econometric model developed by Fezzi et al. (this issue) to explicitly model land-use related agricultural GHG emissions and their value under a high and low emission regime as defined by the UK Climate Impacts Programme (UKCIP 2009) for the period from 2004 to 2060.

The next section outlines the methods used to assess predicted GHG emissions from UK agricultural land between 2004 and 2060. Here we define the system boundaries, the land use change model, the assumptions underpinning our estimates of the resulting GHG emissions and the application of carbon values to those emissions. Section 3 presents the results from the analysis while Section 4 concludes.

Methods and data

Framework of analysis and system boundaries

The analyses are based on the observed and modelled agricultural land use shares (percentages of landscape) within individual 2km grid squares across the United Kingdom. The changes in land uses are obtained by applying the UKCIP low and high GHG emission scenarios (UKCIP 2009) for the years 2020, 2040 and 2060 (together with 2004 as the baseline year) to the structural econometric model of agricultural land use developed by Fezzi and Bateman (2011). The resulting climate induced land use

---

[2] A further potential refinement would be to consider the feedback effects of changes in atmospheric GHG concentrations upon agricultural performance and hence land use. As per previous studies we do not consider such dynamic effects within the present analysis on the grounds that they are likely to be modest given the relatively small scale of UK agriculture.

changes are then used to calculate (i) the annual changes in potential equilibrium carbon stocks in above and below ground biomass across the UK and (ii) the changes in annual emissions (flows) of GHGs which derive from changing the agricultural management or activities resulting from those land use changes. This information is then coupled with potential future carbon values to allow a spatial assessment of the future costs of emissions of agriculture across the UK.

The GHGs included in the analysis were carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) which were converted to CO_2 equivalents (CO_2e). The fermentative digestion (enteric fermentation) in ruminant livestock, stored manures and biomass burning are some of the processes 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 inorganic fertilizers (Smith et al. 2007). The emission of CO_2 occurs from burning of fossil fuels to power of machinery for spraying, spreading, ploughing, harvesting and from the manufacture, packaging and transport of fertilizers and pesticides (Lal 2004).

Each parcel of land (2 by 2km grids) is described in terms of land use shares and livestock numbers (sheep, beef and dairy cattle). SOC_{ik} denotes the soil organic carbon on land use i and soil type k. Soil types (k) were defined as either organic (peat) or non-organic (non-peat),as peat soils have the potential to store considerably greater amounts of carbon that non-organic soils and can release large quantities of carbon if change in land use occurs. $BIOC_i$ describes the above and below ground biomass carbon stock, which is assumed to depend on land use only. Each land use is also associated with a given agricultural management in turn linked to activities, such as tilling, spraying, direct emissions from fertilizers, enteric fermentation and emissions from manures from livestock. Therefore, changes in land use and/or activities will in turn alter our assessment of GHG emissions. However, the analysis does not include introduction of new crops or technological innovation in carbon efficiency.

Land use change model

We implement the structural econometric model introduced by Fezzi and Bateman (2011) and discussed in the context of climate change issue in Fezzi et al (this issue).The data used for estimation were collected on a 2km square grid (400ha) covering the entirety of the UK and encompassing, 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 model includes seven land uses: cereals, oilseed rape, root crops (sugar beet and potatoes), temporary grassland, permanent grassland, rough grazing, and a bundle of other agricultural land-uses (e.g. horticulture, on-farm woodland and bare/fellow land). Due to the lack of spatially explicit data on woodland age, which is a requirement for an accurate spatial modelling of carbon sequestration in woodland (Patenaude et al. 2003), the estimates of on-farm woodland extent in each grid square were subtracted from the “other agriculture” category prior to analysis. Estimates of on-farm woodland extent for each 2km grid were derived from the LCM2000 land cover map (CEH 2000). The removal of on-farm woodland reduced the total agricultural extent in the model by 7% (to 18.4 million hectares), comparing well to official estimates of this area for our 2004 baseline (Defra 2007). The UK climate data used in the models was taken from the spatially explicit (25km square resolution) 2009 UK Climate Impacts Programme climate predictions (UKCIP 2009).

Changes in carbon stocks

The carbon stocks included in the analysis refer to that stored as soil organic carbon (SOC; these being the largest terrestrial carbon stocks in the UK) and in the above and below ground biomass (BIOC; the vegetative stock). While various studies have estimated these stocks across the UK under different land uses (e.g. Bradley et al. 2005; Milne et al. 1997), none have done so at the level of spatial disaggregation used in this analysis or considered the impacts of climate change induced land use change.

The carbon storage capacity of any soil depends upon its characteristics, and contextual factors such as land use, climate, hydrology and topography (Gupta et al. 1994). The current analysis holds the latter two factors constant and only includes climate in respect of its impact upon land use. Following Bradley (2005), national level estimates of average SOC for non-organic soils were used to allow for the different climatic, hydrological and typological differences[3]. It was also assumed that undisturbed UK organic soils, mostly associated with soils under rough grazing, had an average SOC density of 1200 tC/ha (Bateman et al. 2000; Milne et al. 2001).

For each soil type, SOC levels are influenced by land use through its impact on processes such as soil disturbance and nutrient cycling. This was accounted for by applying unique adjustment factors for each land use/soil type combination. Taking data from Cruickshank et al. (1998),non-organic soils under arable land uses (oilseed rape, cereals, roots crops and other agriculture) were assumed to have 84% of the SOC they would attain under improved grassland (temporary and permanent grassland) while soils under rough grazing (semi natural grassland) were defined as having 33% more SOC than improved grasslands (*ibid.*). In comparison, organic (peat) soils under temporary grass and permanent grass were assumed to have an average SOC of 580tC/ha while organic 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 (*ibid.*).[4]

To check the validity of these model assumptions, our estimate of SOC for the UK scenario baseline year (2004) was compared to the most comprehensive estimate of UK SOC by Bradley et al

---

[3] Specifically these were: 132.6 tC/ha for England, 212.2 tC/ha for Northern Ireland, 187.4 tC/ha for Scotland and 142.3 tC/ha for Wales.

[4] Areas of organic soils were identified from European Soil Database (Van Liedekerke et al. 2005). All estimates were based on SOC up to 1m in depth.

(2005). While Bradley et al (2005) estimated the UK SOC stock as 4,563 million tC our estimate resulted in 4,616 million tC; a discrepancy of just 1.3%.[5]

Biomass carbon stocks

Estimates of the biomass carbon stocks (BIOC) for each agricultural land use were taken from Cruickshank et al (1998), Milne and Brown (1997) and Ostle et al (2009). These estimates are based on both above and below ground biomass, with the assumption being that annual BIOC on agricultural lands represent a permanent stock while a particular agricultural land use persists. That is, the biomass lost through harvest in one year is assumed to be replaced by new growth in the subsequent year, implying that net accumulation or loss of BIOC only occurs when land use changes. For the baseline year (2004) it was estimated that the total UK BIOC was 28.82 million tC, this being in broad agreement with the findings of Milne et al (2001) who estimate biomass carbon stocks (excluding woodland stocks) of 22.8 ±5.1 million tC for Great Britain (England, Scotland and Wales only). Table 1 indicates the per hectare estimates of SOC and BIOC for the various different land uses and soil types considered in this analysis.

[Insert Table 1 around here]

Converting from carbon stocks to the annual flow of GHG emissions

The annual net flow of emissions of GHG from land use change comprises two components: (i) Annual SOC fluxes due to agricultural land use change; for example, the conversion of arable land to permanent pasture will result in the accumulation of SOC, while a switch from rough grazing to permanent grassland is likely to reduce SOC. (ii) Annual GHG fluxes from the changes in vegetative biomass associated with land use changes.

A lack of data on land use change prior to the baseline year of 2004 meant that non-organic soils were assumed to have a zero annual SOC flow value during our baseline year. For subsequent years mean equilibrium SOC for non-organic soils was assumed to change from the level associated with the previous land use to that associated with the new land use (see Table 1). SOC accumulation in such soils was assumed to occur linearly over a 100 year period, while SOC emissions were again assumed to be linear although occurring over a 50 year period (Thomson et al. 2007). For example, a hectare of non-

---

[5] The largest discrepancy (5.8%) occurred in Scotland, and is likely to be due to the extensive organic soils found in Scotland and the difficulty in accurately estimated SOC in organic soils due to issues surrounding soil depths along with technical factors associated with the measurement of SOC in organic soils (Chapman et al. 2009).

organic soil in England converted from cereals to permanent grassland was assumed to accumulate 22 tonnes of SOC before it reached a new equilibrium after 100 years, i.e., 0.22tC/ha/yr over the period.

Turning to consider organic soils, annual flows of SOC were estimated for all years including the 2004 baseline as average SOC flow estimates in organic soils are primarily driven by the present agricultural land use rather than changes in land use. For example, annual SOC sequestration rates in organic soils under rough grazing vary from 0.18 tC/ha/yr (Turunen et al. 2002) to 0.36 - 0.73 tC/ha/yr (Worrall et al. 2009). The average of six estimates found in the literature (0.3 tC/ha/yr) was used and it was further assumed that SOC in organic soils under rough grazing would accumulate this quantity of carbon each year. It was assumed that 1.22 tC/ha/yr and 0.61 tC/ha/yr of SOC would be released from organic soils under arable/horticultural land use and improved grassland, respectively (Eggleston et al. 2006).The potential for total exhaustion of the organic matter in organic soils is not considered—i.e. the soil will not reach average non-organic soils SOC equilibrium within the time frame (56 years) considered here—therefore we assume a constant annual release of carbon from organic soils under arable/horticultural land use and improved grassland.

Emissions and accumulations of BIOC were based on the change in vegetative biomass arising from a switch in agricultural land use. The change in equilibrium BIOC estimated for each 2km grid was divided by the time period over which the change occurred to provide an estimate of annual vegetative GHG flux due to land use change. Where the modelled annual BIOC was lower than in the preceding year (within a given 2km grid) then it was considered a net emission of GHGs. It was assumed that the accumulation and emissions of GHGs associated with unchanged land uses were zero, with annual emissions balancing annual sequestration.

GHG emissions from agricultural activities

Three major agricultural sources of annual, per hectare GHG emissions were considered: (i) energy use for typical farming practises such as tillage, sowing, spraying, harvesting as well as the production, storage and transportation of fertilizers and pesticides (estimates taken from Lal, 2004), (ii) emissions of N_2O and methane from livestock, i.e., beef cattle, dairy cows and sheep, through the production of manure and enteric fermentation, and (iii) direct emissions of N_2O emissions from the application of artificial fertilizers.

It was assumed that all arable and horticultural crops require annual conventional tillage, sowing and harvesting. Cereals were assumed to receive two fertilizer and two pesticide applications annually, while three fertilizer and five pesticide applications were assumed for oilseed rape and one fertilizer and four pesticide applications for root crops. Permanent and temporary grasslands were assumed to receive a single fertilizer application and a single harvest (including bailing). Temporary grassland was assumed to be conventionally tilled and sown once every four years. Emissions from farming activities associated with the "other agriculture" land use were taken as the average of the other six land uses.

Per head estimates of livestock GHG emissions from enteric fermentation were based on UK species specific emission factors given by Baggott et al. (2007). Estimates for GHG emissions from livestock manure were derived from Beaton (2006) and Freibauer (2003). Adjusted emissions estimates were applied to direct deposition of manure on grasslands during grazing periods, while emissions from manure spreading (as fertilizer) from housed livestock were estimated from the average grazing days for different livestock types (AEA 2007). Per head estimates of manure production were converted to per grid estimates based on the modelled livestock density across the UK. It was further assumed manure used as fertilizer was utilized within the grid in which it was produced, reducing the requirements for inorganic fertilizers within that grid. Data on per hectare nitrogen requirements for each land use (Beaton 2006) were used to calculate the inorganic fertilizer input requirement for each 2km grid and this was in turn converted to direct emissions of GHG based on estimated N_2O emissions from the application of inorganic fertilizers reported by Kroeze (1994).

Aggregate per hectare GHG emission intensity parameters from agricultural activities and inorganic fertilizer are given in Table 2 while emissions per livestock head appear in Table 3. Total annual GHG emissions within each 2km grid are the sum of the annual SOC and biomass carbon fluxes and the estimated emissions from agricultural activities associated with each land use found within the grid.

[Insert Table 2 around here]
[Insert Table 3 around here]

Valuing GHG emissions

Two approaches to valuation are contrasted in this analysis. First, we apply the Social Cost of Carbon (SCC) function employed by Stern (2007) as appropriate to each emission scenario. Specifically Stern's business as usual (BAU) cost of carbon is applied to the UKCIP high emissions scenario while the low emissions scenario is valued using Stern's 550ppm CO_2e cost of carbon. Both prices are assumed to increase by 2% in real terms annually. For comparison we use the official UK Marginal Abatement Carbon Cost (MACC) approach providing annual non-traded carbon prices out to 2100 (DECC, 2009). This is based on a target constant approach where carbon emissions are assumed to be abated in line with the UK government's domestic carbon emissions target of at least an 80% cut in GHG emissions by 2050 (Climate Change Act 2008). As such the MACC-based carbon prices are not consistent with either the UKCIP low or high emissions scenarios, but costs are based on existing activities and technologies, and can therefore (at least in the present time) be relatively easily estimated (Dietz 2007). Table 4 details these various prices in 2010 values using the UK Treasury's GDP deflator (HM Treasury 2010) and along term exchange rate of \$1.61=£1. A standard conversion ratio of 44:12 was used to convert from £/tC to £/tCO_2e.

[Insert Table 4 around here]

Results

UK terrestrial GHG emissions from agriculture

Figure 1 shows a) emissions from livestock (manures and enteric fermentation), b) the direct GHG emissions (N_2O releases) from inorganic fertilizers application, c) the indirect GHG emissions for agricultural activities including the manufacture and application of external inputs and d) the total GHG emissions from agriculture including annual change in carbon stocks. Taking all these sources together implies annual GHG emissions from agricultural land of 47.2 million tCO_2e for the baseline year of 2004. Such an estimate accords well with other estimates for this year which range from 44.53 million tCO_2e (Thomson et al. 2007) to 51.7 million tCO_2e (DECC 2008). Considering the results presented in Figure 1 we can see that, in the baseline year, enteric fermentation and the direct release of N_2O from artificial and manure fertilisers constituted the major source of agricultural GHG emissions. Overall emissions were highest in the south of England, particularly in the South West, and lowest in the extensively farmed upland areas of the UK.

[Insert Figure 1 around here]

Figure 2 shows the annual changes (from the baseline) in GHG emissions per hectare due to agricultural land use change under the two UKCIP scenarios. Here negative (positive) values represent net reductions (increases) in annual carbon emissions. Both scenarios yield significant changes in annual GHG emissions with lowland areas and in particular the south west of England recording the largest reductions while upland areas exhibit increasing emissions.[6]Such gains can be directly related to the patterns of provisioning service change reported by Fezzi et al (this issue) where upland areas show the largest relative growth in the latter services, a gain which we now see comes at the cost of diminishing regulating services.

---

[6] It should be noted that the results for the south of England are the most prone to uncertainty, because the land use predictions are outside the data used for estimation (see Fezzi et al. this issue).

This is an example of the potential use of the ecosystem service framework to explicitly acknowledge both temporal and spatial trade-offs across different ecosystem services.

[Insert Figure 2 around here]

The increased GHG emissions predicted for the uplands of northern England, Northern Ireland, Scotland and Wales are primarily due to increased livestock numbers (predominantly dairy herds) and increases in arable and horticultural production as climate change makes these areas more suitable for such activities. The conversion of agricultural land on organic soils from rough grazing to improved, temporary and permanent grassland also represents a large source of increased GHG emissions. In contrast, the conversion of arable land, particularly cereals, to grasslands in southern regions of the UK leads to net reductions in emissions compared to the baseline in such regions. Figure 3 identifies regional changes in the predicted per hectare GHG emissions for the two UKCIP climate change scenarios. A geographical divide is apparent with falling emissions in southern regions and increasing emissions in the north.

[Insert Figure 3 here]

In contrast to the highly significant spatial and temporal trends revealed by our findings, comparison across the low and high emission scenarios shows that this makes relatively little difference to analytical results. The higher emission scenario mainly serves enhance the trends observed in its lower counterpart such that emission increases in upland areas become greater as do the reductions occurring in lowlands. Overall the latter outweighs the former such that after 2020 aggregate emission increases are inversely related to the degree of climate change.Table 5 provides a more detailed analysis of the predicted change in UK annual agricultural GHG emissions under both climate change scenarios.

[Insert Table 5 around here]

The model predicts the increase in agricultural GHG emissions over time to be largely driven by from livestock and agricultural activities as rough grazing land in the north and arable land in the south are converted to temporary and permanent grasslands for dairy farming (all regions) and beef production (Scotland). Aggregate changes in GHG emissions due to changing stocks of SOC and biomass carbon as a result of changing land use patterns are relatively small in all analysis years, with the exception of 2060 under the UKCIP high emissions scenario where predicted conversion from arable to grassland on organic soils results in considerable net accumulations of SOC. In all scenarios the main source of annual changes in carbon stocks comes from loss of SOC in organic soils rather than changes in carbon stocks stored in biomass.

Valuation of predicted GHG emissions for agriculture

The prices in Table 4 are used to estimate the total annual cost of agricultural GHG emissions under the two UKCIP climate scenarios. Results of this analysis are reported in Table 6 where positive values represent costs of increasing emissions, i.e. reductions in regulatory ecosystem services. For ease of real value comparison we report these as undiscounted amounts (in 2010 prices) reflecting the cost of emissions in the specified year in which those emissions occur.

[Insert table 6 around here]

Table 6 reports annual costs of GHG emissions arising from climate induced changes in UK agriculture. As can be seen, irrespective of the climate scenario or pricing mode, as time passes overall costs rise. However, while these increases are substantial across time, cost estimates vary markedly according to the carbon price adopted. Adoption of the Stern 550ppm social cost of carbon (SCC) function results in annual value estimates which are far lower than under any other price/scenario combination as the estimated unit cost of carbon under this scenario is significantly lower due to the assumed stabilisation of global climate associated with limiting the increase of global temperatures to 2 degrees Celsius.

Figure 4 represents the predicted annual and cumulative costs of the net flow of UK agricultural GHG emissions for the UKCIP high emissions scenario based on the DECC carbon price function. The net emission intensity of GHGs per area of agricultural land is predicted to decline in England, Wales and Northern Ireland after 2040 (Figure 4(a)) implying an increase in the climate regulatory services. Extending the time horizon to 2060 changes results significantly. The costs of emissions (global dis-service) increase sharply until 2060 (Figure 4(b)). Agricultural GHG costs are predicted to reach £1000/ha in Northern Ireland by 2060 and around £800/ha in both Scotland and Wales. In England emission costs increase from around in £100/ha in 2004 to around £480/ha in 2060. The accumulated total costs of GHG emissions from agriculture between 2004 and 2060 are around £140 billion for England, £24 billion for Northern Ireland, £127 billion for Scotland and £30 billion for Wales(Figure 4(d)). Therefore, even the sharp falls in GHG emissions in England may be insufficient to offset the increased cost of carbon imposed on UK agriculture.

[Insert Figure 4 around here]

Table 7 presents a disaggregated regional analysis of the predicted annual per hectare cost of agricultural GHG emissions based on the DECC price function for the two UKCIP emissions scenarios. Here the figures in brackets represent the percentage change in carbon costs that are due to climate induced land use change. As such the bracketed values indicate the expected impact on the cost of agricultural GHG emissions in the UK solely due to the land use adjustments induced by global climate change. For instance, in the low emissions scenario, by 2060 the climate induced land use change in south east England is predicted to reduce the average cost of GHG emissions by £257$ha^{-1}yr^{-1}$ to a net impact of £364 $ha^{-1}yr^{-1}$ compared to the expected cost of emissions if such land use response did not occur (£621 $ha^{-1}yr^{-1}$). The analysis therefore shows the impact of climate change on GHG emissions in UK agriculture by region, controlling for land use change adjustments that would take place in response to exogenous changes in climate. Note that technical change and agricultural commodity are held constant in this analysis and changes in these variables are likely to induce variations from our predictions.

[Insert Table 7 around here]

Table 7 also indicates the inability of even large regional reductions in agricultural emissions to offset rising per unit carbon cost in the UK based on DECC price function. For example, while the east of England is predicted to see a significant(68%) physical reduction in annual GHG emissions between 2004 and 2060 (under the high emission scenario), the predicted per hectare cost of emissions will still more than double over that time period due to rising carbon prices. The situation in regions with predicted increases in GHG emissions is potentially even more problematic with carbon costs in Scotland under the high emissions scenario climbing from £100 per hectare in 2004 to almost £800 per hectare in 2060.

Conclusions

This article assesses the physical and economic value of changes in GHG emissions from agricultural land in the UK during the period 2004-2060 under different climate change scenarios. Fezzi et al in this issue assess the changes in the value of provisioning services over time based on climatic scenarios. This paper takes those same scenarios and computes the value of climate regulation in UK agriculture over the same time-span (2004-2060). Together these two papers cast new light on the role of agriculture as a source of both provisioning and regulating ecosystem services.

It is suggested that agricultural responses to climate change over the next 50 years may lead to significant changes in UK land use and a sharp regional disparity resultant changes to GHG emissions. This information is important to predict the associated carbon regulating ecosystem service cost from agriculture over time. The spatial analysis indicates that northern parts of the UK are expected to see decreases in potential carbon stocks and rising GHG emissions due to increased agricultural intensification as the climate warms. In contrast the southern parts of the UK are predicted to see small increases in carbon stocks and associated falls in annual agricultural emissions as cereal crops are edged out by rough grazing in a drier hotter future. Overall, these changes may have significant impacts on UK attempts to decrease GHG emissions, as agricultural emissions are, *ceteris paribus*, estimated to increase by around 11% over the next decade when climate-induced agricultural land use change are factored in.

The results of this analysis suggest that global climate change induced adjustments in land use will, in some regions of the UK, help mitigate agricultural GHG emissions, while in others it will have the opposite effect. The results also show that even in regions where agricultural emissions are expected to decline over time, this will be more than offset by escalating marginal values of carbon. This suggests that the agricultural sector has the potential to contribute towards climate change mitigation but such activities will not translate into social benefits from land use adjustments alone.

The spatially heterogeneous agricultural land use and emission changes in response to climate change, combined with the increasing cost of carbon suggest the need for integrated spatio-temporal modelling response. Such analytic tools are likely to become increasingly important as decision makers face the challenges of optimising ecosystem service delivery in a world of climate change and increasing resource austerity.

Acknowledgements

The research presented in this paper was conducted as part of the UK National Ecosystem Assessment. Funding was in part provided by the Social and Environmental Economic Research (SEER) into Multi-Objective Land Use Decision Making project (in turn funded by the Economic and Social Research Council (ESRC); Funder Ref: RES-060-25-0063).

References

AEA (2007) Research into the current and potential climate change mitigation impacts of environmental stewardship. Hatfield: Agriculture & Environment Research Unit.

Baggott SL,Cardenas L et al (2007) Greenhouse Gas Inventories for England, Scotland, Wales and Northern Ireland; 1990-2005. National Environmental Technology Centre, AEA technology Centre.

Bateman IJ, Lovett AA (2000) Estimating and valuing the carbon sequestered in softwood and hardwood trees, timber products and forest soils in Wales, Journal of Environmental Management 60:301-323.

Beaton C, editor. (2006) The Farm Management Handbook 2006/7. Edinburgh: SAC.

Bradley RI,Milne R et al (2005) A soil carbon and land use database for the United Kingdom. Soil Use and Management 21(4):363-369.

CEH (2000) Centre for Ecology and Hydrology Land Cover Map.

Chapman SJ,Bell J et al (2009) Carbon stocks in Scottish peatlands. Soil Use and Management 25(2):105-112.

Climate Change Act (2008) Climate Change Act 2008. lONDON: HMSO.

Cruickshank MM,Tomlinson RW et al (1998) Carbon in the vegetation and soils of Northern Ireland. Biology and Environment-Proceedings of the Royal Irish Academy 98B(1):9-21.

Dale VH (1997) The relationship between land-use change and climate change. Ecological Applications 7(3):753-769.

Dasgupta, P. (2006). Comments on the Stern Review's Economics of Climate Change, University of Cambridge.

DECC (2008) 2008 final UK greenhouse gas emissions: data tables. In: DECC, editor. London: DECC.

DECC (2009a) Carbon valuation in UK policy appraisal: a revised approach. London: Departmant of Energy and Climate Change.

DECC (2009b) Guidance on estimating carbon values beyond 2050: an iterim approach. London: Departmant of Energy and Climate Change.

DEFRA (2007) Land by agricultural and other uses: 2004. London: Department for Environment, Food and Rural Affairs

Dietz S (2007) Review of DEFRA paper: “The social cost of carbon and the shadow price of carbon: what they are, and how to use them in economic appraisal in the UK”. London: Department of Environment, Farming and Rural Affairs.

Downing TE,Anthoff D et al (2005) Scoping uncertainty in the social cost of carbon. In: Department of Environment FaRA, editor. London.

EEA (2005). Agriculture and environment in EU-15— the IRENA indicator report. European Environmetnal Agency Report No 6/2005. Cophenhagen, Denmark.

Eggleston HS,Buendia L et al (2006) Guidelines for National Greenhouse Gas Inventories Hayama: IGES.

Ekins P (2007) Peer review of DEFRA's paper The social cost of carbon and the shadow price of carbon: what they are, and how to use them in economic appraisal in the UK. London: Department of Environment, Farming and Rural Affairs.

Erb KH (2004) Land-use related changes in aboveground carbon stocks of Austria's terrestrial ecosystems. Ecosystems 7(5):563-572.

Fezzi, C. and Bateman, I.J. (2011) Structural agricultural land use modeling for spatial agro-environmental policy analysis, *American Journal of Agricultural Economics* 93:1168-1188.

Fezzi C, Bateman I, Askew, T., Munday, P, Pascual, U., Sen, A., Darnell, A. (this issue). Valuing provisioning ecosystem services in agriculture: a climate scenario analysis for the United Kingdom

Foley JA,DeFries R et al (2005) Global consequences of land use. Science 309(5734):570-574.

Freibauer A (2003) Regionalised inventory of biogenic greenhouse gas emissions from European agriculture. European Journal of Agronomy 19(2):135-160.

Gupta RK, Rao DLN (1994) Potential of wastelands for sequestering carbon by reforestation. Current Science 66(5):378-380.

Hediger W (2006) Modeling GHG emissions and carbon sequestration in Swiss agriculture: An integrated economic approach. International Congress Series 1293:86-95.

HM Treasury (2010) UK Gross Domestic Product (GDP) deflators. London: HMSO.

IPCC (2006) IPCC guidelines for national Greenhouse gas Inventories, Prepared by the national Green house Gas Inventories: Published IGES, Japan.

Kroeze C (1994) Nitros Oxide (N2O) emissions Inventory and options for control in the Nertherlands: National Insititute of Public Health and Environmental Protection (RIVM).

Lal R (2004) Carbon emission from farm operations. Environment International 30(7):981-990.

Marland G,Pielke RA et al (2003) The climatic impacts of land surface change and carbon management, and the implications for climate-change mitigation policy. Climate Policy 3(2):149-157.

McLeod, M. Moran D, Eory, V, Rees, R.M., Barnes, A., Topp, C.F.E., Ball, B, Hoad, S., Wall, E., McVittie, A., Pajot, G., Matthews, R., Smith, P. Moxey, A., (2010) Developing greenhouse gas marginal abatement cost curves for agricultural emissions from crops and soils in the UK. Agricultural Systems: 103: 198-209

Milne R, Brown TA (1997) Carbon in the Vegetation and Soils of Great Britain. Journal of Environmental Management 49(4):413-433.

Milne R,Tomlinson RW et al (2001) The land use change and forestry sector in the 1999 UK greenhouse gas inventory. Annual report for DETR Contract EPG1/1/160. In: Milne R (ed). UK Emissions by sources and removals by sinks due to land use land use change and forestry activities. DEFRA, London

Moran D,MacLeod M et al (2011) Developing carbon budgets for UK agriculture, land-use, land-use change and forestry out to 2022. Climatic Change 105(3-4):529-553.

Mosier AR,Duxbury JM et al (1998) Mitigating agricultural emissions of methane. Climatic Change 40:39-80.

Nordhaus, W. (2008). A Question of Balance. Weighing the Options on Global Warming Policies. Yale University Press

Office of National Statistics (2006) United Kingdom National Accounts The Blue Book In: Statistics OoN, editor. Basingstoke: Palgrave Macmillan. p P210.

Ostle NJ,Levy PE et al (2009) UK land use and soil carbon sequestration. Land Use Policy 26:S274-S283.

Patenaude GL,Briggs BDJ et al (2003) The carbon pool in a British semi-natural woodland. Forestry 76(1):109-119.

Pretty J, Ball B (2001) Agricultural Influences on Carbon emissions and Sequestration: A Review of Evidence and the Emerging Trading Options. Centre for Environment and Society Occasional Paper 2001-2003, University of Essex.

Risbey,R. Kandlikar, M., Dowlabadi, H, Graetz, D. (1999). Scale, context, and decision making in agricultural adaptation to climate variability and change, Mitigation and Adaptation Strategies for Global Change 4(2): 137-165

Rounsevell MDA, Reay DS (2009) Land use and climate change in the UK. Land Use Policy 26:S160-S169.

Seo SN, Mendelsohn R (2008) An analysis of crop choice: Adapting to climate change in South American farms. Ecological Economics 67(1):109-116.

Smith P (2004) Carbon sequestration in croplands: the potential in Europe and the global context. European Journal of Agronomy 20(3):229-236.

Smith P,Martino D et al (2007) Policy and technological constraints to implementation of greenhouse gas mitigation options in agriculture. Agriculture, Ecosystems & Environment 118(1-4):6-28.

Smith P,Martino D et al (2008) Greenhouse gas mitigation in agriculture. Philosophical Transactions of the Royal Society B: Biological Sciences 363(1492):789-813.

Stern N (2007) The economics of climate change: the Stern review. Cambridge University Press, Cambridge

Thomas J,Thistlethwaite G et al (2011) Greenhouse gas inventories for England, Scotland, Wales and Northern Ireland: 1990 - 2009. Didcot: Department of Energy and Climate Change, The Scottish Government, The Welsh Government, The Northern Ireland Department of Environment.

Thomson AM,Mobbs DC et al (2007) Annual inventory estimates for the UK London: Centre for Ecology and Hydrology/DEFRA.

Turunen J,Tomppo E et al (2002) Estimating carbon accumulation rates of undrained mires in Finland - application to boreal and subarctic regions. Holocene 12(1):69-80.

UKCIP (2009) UK climate projection: briefing report. In: Programme UCI, editor. Exeter, UK: Met Office Hadley Centre.

Van Liedekerke M, Panagos P (2005) ESDBv2 Raster Archive - a set of rasters derived from the European Soil Database distribution version 2 Brussels: European Commission and the European Soil Bureau Network. p CD-ROM, EUR 19945 EN

West TO, Marland G (2003) Net carbon flux from agriculture: Carbon emissions, carbon sequestration, crop yield, and land-use change. Biogeochemistry 63(1):73-83.

Worrall F,Bell MJ et al (2009) Assessing the probability of carbon and greenhouse gas benefit from the management of peat soils. Science of the Total Environment 408(13):2657-2666.

Figures

Figure 1 Estimated GHG fluxes from UK agriculture for the baseline year (2004)

Figure 2 Predicted changes from the baseline in per hectare UK agricultural GHG emissions under two UKCIP climate change scenarios

Figure 3 Regional changes in predicted per hectare agricultural GHG emissions under two UKCIP climate change scenarios

Figure 4 Predicted annual and cumulative costs of UK agricultural GHG emissions under the UKCIP high emissions scenario with DECC carbon prices

Table 1 Estimates of SOC and BIOC for different agricultural land uses in the UK

Agricultural land uses	Carbon stored in above and below ground biomass on non-organic/organic soils (tC/ha)	SOC England non-organic/organic soils (tC/ha)	SOC Scotland non-organic/organic soils (tC/ha)	SOC Wales non-organic/organic soils (tC/ha)	SOC Northern Ireland non-organic/organic soils (tC/ha)
Oilseed rape	1.8/1.8	111/133	157/187	120/142	178/212
Cereals	2.4/2.4	111/133	157/187	120/142	178/212
Root crops	2.5/2.5	111/133	157/187	120/142	178/212
Other agriculture	1.4/1.4	111/133	157/187	120/142	178/212
Temporary grass	0.9/0.9	133/580	187/580	142/580	212/580
Permanent grass	0.9/0.9	133/580	187/580	142/580	212/580
Rough grazing	1.66/2.0	176/1200	249/1200	189/1200	282/1200

(Sources Bateman et al. 2000; Bradley et al. 2005; Cruickshank et al. 1998; Milne et al. 2001)

Table 2 GHG emissions from farm activities related to different agricultural land uses

Agricultural land use	Emissions from agricultural activities (tCO_2e/ha/yr)	N_2O emissions from inorganic fertilizer applications (tCO_2e/ha/yr)
Cereals	0.55	0.95
Oilseed rape	0.48	1.06
Root crops	0.46	1.01
Temporary grass	0.48	1.27
Permanent grass	0.35	0.89
Rough grazing	0	0.00
Other agriculture	0.4	1.03

(Sources IPCC 2006; Kroeze 1994; Lal 2004)

Table 3 GHG emissions per head from livestock

Livestock	Enteric fermentation (tCO_2e/head/yr)	Emissions from manure deposited directly onto grasslands (tCO_2e/head/yr)	Emissions from manure used as fertilizer (tCO_2e/head/yr)
Dairy	2.381	0.145	0.016
Beef	1.104	0.086	0.006
Sheep	0.184	0.054	0.001

(sources Beaton 2006; DEFRA 2007; Freibauer 2003; IPCC 2006)

Table 4 Carbon pricing (2010 prices)

Year	Stern 550 ppm emissions trajectory (£/tCO$_2$e)	Stern BAU emissions trajectory (£/tCO$_2$e)	DECC 2009 (£/tCO$_2$e)
2004	£25.47	£88.38	£44.69
2020	£34.96	£121.32	£58.29
2040	£51.95	£180.28	£131.15
2060	£77.20	£267.89	£258.41

(Sources DECC 2009b; Stern 2007)

Table 5 Predicted UK agricultural GHG emissions under UKCIP low and high emission scenarios (million tCO_2e/yr)

Year	emissions from manures and enteric fermentation	emissions from agricultural activities (including N_2O from inorganic fertilizers)	emissions from annual changes in carbon stocks in SOC and biomass	total emissions
baseline (2004)	18.80	16.81	11.61	47.22
UKCIP low emissions scenario				
2020	21.40	18.42	12.93	52.74
2040	21.29	18.66	12.36	52.31
2060	20.63	18.57	12.42	51.63
UKCIP high emissions scenario				
2020	21.53	18.36	11.54	51.43
2040	21.22	18.55	11.89	51.66
2060	20.48	17.64	7.00	45.12
predicted total accumulated GHG emissions from UK agriculture (million tCO_2e)				
UKCIP low emissions scenario				
2004-2020	323	281	185	789
2004-2040	750	650	419	1,820
2004-2060	1,167	1,012	608	2,788
UKCIP high emissions scenario				
2004-2020	323	281	185	789
2004-2040	750	650	419	1,820
2004-2060	1,167	1,012	608	2,788

Table 6 Predicted, undiscounted annual costs of UK agricultural GHG emissions under two UKCIP climate scenarios (2010 prices)

Price function	2004 (billion £/yr)	2020 (billion £/yr)	2040 (billion £/yr)	2060 (billion £/yr)
UKCIP low emissions scenario				
DECC MACC	2.11	3.07	6.86	13.34
Stern low (550ppm) SCC	1.20	1.84	2.72	3.99
UKCIP high emissions scenario				
DECC MACC	2.11	3.00	6.77	11.66
Stern high (BAU) SCC	4.17	6.24	9.31	12.09

Table 7 Average regional agricultural carbon costs (£/ha/yr) in the UK based on the DECC carbon price function (in 2010 prices).

		UKCIP low emissions scenario			UKCIP high emissions scenario		
Region	Baseline 2004 (£/ha/yr)	2020 (£/ha/yr)	2040 (£/ha/yr)	2060 (£/ha/yr)	2020 (£/ha/yr)	2040 (£/ha/yr)	2060 (£/ha/yr)
Scotland	£100	£174 (£43)	£410 (£115)	£843 (£262)	£165 (£34)	£413 (£118)	£798 (£217)
Wales	£115	£185 (£36)	£419 (£83)	£819 (£157)	£178 (£29)	£418 (£82)	£756 (£94)
Northern Ireland	£151	£225 (£29)	£516 (£74)	£1,021 (£150)	£221 (£25)	£516 (£74)	£954 (£83)
North East	£121	£192 (£33)	£442 (£86)	£877 (£175)	£188 ($29)	£443 (£86)	£744 (£42)
North West	£148	£225 (£32)	£514 (£78)	£1,013 (£154)	£219 (£26)	£512 (£76)	£918 (£59)
Yorkshire Humber	£118	£168 (£14)	£371 (£24)	£709 (£27)	£166 (£12)	£365 (£19)	£595 (-£87)
East Midlands	£100	£120 (-£10)	£242 (-£50)	£432 (-£144)	£120 (-£10)	£231 (-£62)	£337 (-£240)
West Midlands	£117	£142 (-£11)	£289 (-£55)	£509 (-£169)	£143 (-£10)	£275 (-£62)	£389 (-£240)
East of England	£108	£116 (-£25)	£231 (-£87)	£409 (-£217)	£116 (-£25)	£219 (-£99)	£227 (-£399)
South East	£108	£111 (-£29)	£217 (-£87)	£364 (-£257)	£116 (-£24)	£201 (-£114)	£248 (-£374)
South West	£138	£172 (-£8)	£359 (-£45)	£642 (-£153)	£173 (-£7)	£344 (-£60)	£488 (-£307)
London	£109	£104 (-£38)	£208 (-£111)	£345 (-£284)	£112 (-£29)	£194 (-£125)	£229 (-£400)
UK	£115	£167 (£17)	£372 (£36)	£724 (£62)	£163 (£13)	£368 (£32)	£633 (-£29)

Figures in brackets represent the cost of climate regulation dis-service related to the adjustment in land use change to climate change.