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2 **Valuing climate change effects upon UK agricultural GHG emissions:**
3 **Spatial analysis of a regulating ecosystem service**
4

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15
16 **Abstract**

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

24
25 **Keywords:** Climate change, GHG emissions, ecosystem services, land use change, agriculture.
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29 **Introduction**

30 Roughly 77% of UK land is under agricultural production (Defra, 2007), with its primary purpose being
31 the provision of food and fibre. However, the conversion and management of land for such provisioning
32 purposes typically also impacts upon the provision of other ecosystem services. One of the major
33 impacts of agricultural land management and conversion is upon the ability of the land to contribute to
34 climate regulation through the accumulation of atmospheric CO₂ as carbon in biomass and soil organic
35 carbon (SOC). Agricultural land uses differ both in their capacity to store carbon and in the direct and
36 indirect emissions of greenhouse gases (GHGs) associated with the management of those land uses.
37 Agriculture accounts for approximately 9% of the UK's net greenhouse gas (GHG) emissions¹(Thomas
38 et al. 2011); a figure which is near to the average for the EU-15 nations (EEA, 2005).

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

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

¹Reference to greenhouse gas (GHG) emissions is often made in terms of carbon (or tonnes of carbon) as shorthand for CO₂ or the equivalent of other GHGs (CO₂e) in the atmosphere. For the sake of expediency we will follow this convention here. Additionally, the term unit cost or price of CO₂e, is used interchangeably for the notion of the marginal value of a reduction of a tonne of CO₂e whether it is transacted in the market or not.

61 climate change through changes in land use and consider the impact that those land use changes will
62 have on GHG emissions².

63 Economic assessment of variations in the GHG regulatory services arising from agricultural
64 change relies on estimates of the value of carbon emissions or mitigation. A vibrant literature has
65 provided a framework for such analysis (e.g., Downing et al. 2005; Dasgupta; 2006, Ekins 2007; Stern,
66 2007; Nordhaus, 2008). This notes that for scenario analyses future carbon prices are dependent on the
67 assumed emission trajectory, abatement technology, discount rates and the adopted climate projections
68 (DECC 2009a). As such, future carbon prices are endogenous to the emission and climate scenarios upon
69 which they are based.

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

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

84 **Methods and data**

85 *Framework of analysis and system boundaries*

86 The analyses are based on the observed and modelled agricultural land use shares (percentages of
87 landscape) within individual 2km grid squares across the United Kingdom. The changes in land uses are
88 obtained by applying the UKCIP low and high GHG emission scenarios (UKCIP 2009) for the years
89 2020, 2040 and 2060 (together with 2004 as the baseline year) to the structural econometric model of
90 agricultural land use developed by Fezzi and Bateman (2011). The resulting climate induced land use

²A 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.

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

96 The GHGs included in the analysis were carbon dioxide (CO₂), methane (CH₄) and nitrous oxide
97 (N₂O) which were converted to CO₂ equivalents (CO₂e). The fermentative digestion (enteric
98 fermentation) in ruminant livestock, stored manures and biomass burning are some of the processes
99 which result in the production of methane (Mosier et al. 1998). Nitrous oxide (N₂O) is released by the
100 microbial action on nitrogen in the soils, manures and from the application of inorganic fertilizers (Smith
101 et al. 2007). The emission of CO₂ occurs from burning of fossil fuels to power of machinery for
102 spraying, spreading, ploughing, harvesting and from the manufacture, packaging and transport of
103 fertilizers and pesticides (Lal 2004).

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

114

115 *Land use change model*

116 We implement the structural econometric model introduced by Fezzi and Bateman (2011) and
117 discussed in the context of climate change issue in Fezzi et al (this issue). The data used for estimation
118 were collected on a 2km square grid (400ha) covering the entirety of the UK and encompassing, for the
119 past 40 years: (a) the share of each land use and the numbers of livestock, (b) environmental and climatic
120 characteristics, (c) policy and other drivers. The model includes seven land uses: cereals, oilseed rape,
121 root crops (sugar beet and potatoes), temporary grassland, permanent grassland, rough grazing, and a
122 bundle of other agricultural land-uses (e.g. horticulture, on-farm woodland and bare/fallow land). Due to
123 the lack of spatially explicit data on woodland age, which is a requirement for an accurate spatial
124 modelling of carbon sequestration in woodland (Patenaude et al. 2003), the estimates of on-farm
125 woodland extent in each grid square were subtracted from the “other agriculture” category prior to
126 analysis. Estimates of on-farm woodland extent for each 2km grid were derived from the LCM2000 land

127 cover map (CEH 2000). The removal of on-farm woodland reduced the total agricultural extent in the
128 model by 7% (to 18.4 million hectares), comparing well to official estimates of this area for our 2004
129 baseline (Defra 2007). The UK climate data used in the models was taken from the spatially explicit
130 (25km square resolution) 2009 UK Climate Impacts Programme climate predictions (UKCIP 2009).

131 *Changes in carbon stocks*

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

137 The carbon storage capacity of any soil depends upon its characteristics, and contextual factors
138 such as land use, climate, hydrology and topography (Gupta et al. 1994). The current analysis holds the
139 latter two factors constant and only includes climate in respect of its impact upon land use. Following
140 Bradley (2005), national level estimates of average SOC for non-organic soils were used to allow for the
141 different climatic, hydrological and typological differences³. It was also assumed that undisturbed UK
142 organic soils, mostly associated with soils under rough grazing, had an average SOC density of 1200
143 tC/ha (Bateman et al. 2000; Milne et al. 2001).

144 For each soil type, SOC levels are influenced by land use through its impact on processes such
145 as soil disturbance and nutrient cycling. This was accounted for by applying unique adjustment factors
146 for each land use/soil type combination. Taking data from Cruickshank et al. (1998), non-organic soils
147 under arable land uses (oilseed rape, cereals, roots crops and other agriculture) were assumed to have
148 84% of the SOC they would attain under improved grassland (temporary and permanent grassland) while
149 soils under rough grazing (semi natural grassland) were defined as having 33% more SOC than
150 improved grasslands (*ibid.*). In comparison, organic (peat) soils under temporary grass and permanent
151 grass were assumed to have an average SOC of 580tC/ha while organic soils under arable land uses were
152 assumed to have long term equilibrium SOC equal to the average non-organic soil SOC of the region
153 within which the soils are located (*ibid.*).⁴

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

³Specifically 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.

156 (2005). While Bradley et al (2005) estimated the UK SOC stock as 4,563 million tC our estimate
157 resulted in 4,616 million tC; a discrepancy of just 1.3%.⁵

158 *Biomass carbon stocks*

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

170

171 [Insert Table 1 around here]

172 *Converting from carbon stocks to the annual flow of GHG emissions*

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

178 A lack of data on land use change prior to the baseline year of 2004 meant that non-organic soils
179 were assumed to have a zero annual SOC flow value during our baseline year. For subsequent years
180 mean equilibrium SOC for non-organic soils was assumed to change from the level associated with the
181 previous land use to that associated with the new land use (see Table 1). SOC accumulation in such soils
182 was assumed to occur linearly over a 100 year period, while SOC emissions were again assumed to be
183 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).

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

186 Turning to consider organic soils, annual flows of SOC were estimated for all years including
187 the 2004 baseline as average SOC flow estimates in organic soils are primarily driven by the present
188 agricultural land use rather than changes in land use. For example, annual SOC sequestration rates in
189 organic soils under rough grazing vary from 0.18 tC/ha/yr (Turunen et al. 2002) to 0.36 - 0.73 tC/ha/yr
190 (Worrall et al. 2009). The average of six estimates found in the literature (0.3 tC/ha/yr) was used and it
191 was further assumed that SOC in organic soils under rough grazing would accumulate this quantity of
192 carbon each year. It was assumed that 1.22 tC/ha/yr and 0.61 tC/ha/yr of SOC would be released from
193 organic soils under arable/horticultural land use and improved grassland, respectively (Eggleston et al.
194 2006).The potential for total exhaustion of the organic matter in organic soils is not considered—i.e. the
195 soil will not reach average non-organic soils SOC equilibrium within the time frame (56 years)
196 considered here—therefore we assume a constant annual release of carbon from organic soils under
197 arable/horticultural land use and improved grassland.

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

205 *GHG emissions from agricultural activities*

206 Three major agricultural sources of annual, per hectare GHG emissions were considered: (i) energy use
207 for typical farming practises such as tillage, sowing, spraying, harvesting as well as the production,
208 storage and transportation of fertilizers and pesticides (estimates taken from Lal, 2004), (ii) emissions of
209 N₂O and methane from livestock, i.e., beef cattle, dairy cows and sheep, through the production of
210 manure and enteric fermentation, and (iii) direct emissions of N₂O emissions from the application of
211 artificial fertilizers.

212 It was assumed that all arable and horticultural crops require annual conventional tillage, sowing
213 and harvesting. Cereals were assumed to receive two fertilizer and two pesticide applications annually,
214 while three fertilizer and five pesticide applications were assumed for oilseed rape and one fertilizer and
215 four pesticide applications for root crops. Permanent and temporary grasslands were assumed to receive
216 a single fertilizer application and a single harvest (including bailing). Temporary grassland was assumed

217 to be conventionally tilled and sown once every four years. Emissions from farming activities associated
218 with the “other agriculture” land use were taken as the average of the other six land uses.

219 Per head estimates of livestock GHG emissions from enteric fermentation were based on UK
220 species specific emission factors given by Baggott et al. (2007). Estimates for GHG emissions from
221 livestock manure were derived from Beaton (2006) and Freibauer (2003). Adjusted emissions estimates
222 were applied to direct deposition of manure on grasslands during grazing periods, while emissions from
223 manure spreading (as fertilizer) from housed livestock were estimated from the average grazing days for
224 different livestock types (AEA 2007). Per head estimates of manure production were converted to per
225 grid estimates based on the modelled livestock density across the UK. It was further assumed manure
226 used as fertilizer was utilized within the grid in which it was produced, reducing the requirements for
227 inorganic fertilizers within that grid. Data on per hectare nitrogen requirements for each land use (Beaton
228 2006) were used to calculate the inorganic fertilizer input requirement for each 2km grid and this was in
229 turn converted to direct emissions of GHG based on estimated N₂O emissions from the application of
230 inorganic fertilizers reported by Kroeze (1994).

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

236

237 [Insert Table 2 around here]

238 [Insert Table 3 around here]

239 *Valuing GHG emissions*

240 Two approaches to valuation are contrasted in this analysis. First, we apply the Social Cost of Carbon
241 (SCC) function employed by Stern (2007) as appropriate to each emission scenario. Specifically Stern’s
242 business as usual (BAU) cost of carbon is applied to the UKCIP high emissions scenario while the low
243 emissions scenario is valued using Stern’s 550ppm CO₂e cost of carbon. Both prices are assumed to
244 increase by 2% in real terms annually. For comparison we use the official UK Marginal Abatement
245 Carbon Cost (MACC) approach providing annual non-traded carbon prices out to 2100 (DECC, 2009).
246 This is based on a target constant approach where carbon emissions are assumed to be abated in line with
247 the UK government’s domestic carbon emissions target of at least an 80% cut in GHG emissions by
248 2050 (Climate Change Act 2008). As such the MACC-based carbon prices are not consistent with either
249 the UKCIP low or high emissions scenarios, but costs are based on existing activities and technologies,
250 and can therefore (at least in the present time) be relatively easily estimated (Dietz 2007). Table 4 details
251 these various prices in 2010 values using the UK Treasury’s GDP deflator (HM Treasury 2010) and

252 along term exchange rate of \$1.61=£1. A standard conversion ratio of 44:12 was used to convert from
253 £/tC to £/tCO₂e.

254

255 [Insert Table 4 around here]

256

257 **Results**

258 *UK terrestrial GHG emissions from agriculture*

259 Figure 1 shows a) emissions from livestock (manures and enteric fermentation), b) the direct GHG
260 emissions (N₂O releases) from inorganic fertilizers application, c) the indirect GHG emissions for
261 agricultural activities including the manufacture and application of external inputs and d) the total GHG
262 emissions from agriculture including annual change in carbon stocks. Taking all these sources together
263 implies annual GHG emissions from agricultural land of 47.2 million tCO₂e for the baseline year of
264 2004. Such an estimate accords well with other estimates for this year which range from 44.53 million
265 tCO₂e (Thomson et al. 2007) to 51.7 million tCO₂e (DECC 2008). Considering the results presented in
266 Figure 1 we can see that, in the baseline year, enteric fermentation and the direct release of N₂O from
267 artificial and manure fertilisers constituted the major source of agricultural GHG emissions. Overall
268 emissions were highest in the south of England, particularly in the South West, and lowest in the
269 extensively farmed upland areas of the UK.

270

271 [Insert Figure 1 around here]

272

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

⁶It 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).

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

283

284 [Insert Figure 2 around here]

285

286 The increased GHG emissions predicted for the uplands of northern England, Northern Ireland, Scotland
287 and Wales are primarily due to increased livestock numbers (predominantly dairy herds) and increases in
288 arable and horticultural production as climate change makes these areas more suitable for such activities.

289 The conversion of agricultural land on organic soils from rough grazing to improved, temporary and
290 permanent grassland also represents a large source of increased GHG emissions. In contrast, the
291 conversion of arable land, particularly cereals, to grasslands in southern regions of the UK leads to net
292 reductions in emissions compared to the baseline in such regions. Figure 3 identifies regional changes in
293 the predicted per hectare GHG emissions for the two UKCIP climate change scenarios. A geographical
294 divide is apparent with falling emissions in southern regions and increasing emissions in the north.

295

296 [Insert Figure 3 here]

297

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

305

306 [Insert Table 5 around here]

307

308 The model predicts the increase in agricultural GHG emissions over time to be largely driven by from
309 livestock and agricultural activities as rough grazing land in the north and arable land in the south are
310 converted to temporary and permanent grasslands for dairy farming (all regions) and beef production
311 (Scotland). Aggregate changes in GHG emissions due to changing stocks of SOC and biomass carbon as
312 a result of changing land use patterns are relatively small in all analysis years, with the exception of 2060

313 under the UKCIP high emissions scenario where predicted conversion from arable to grassland on
314 organic soils results in considerable net accumulations of SOC. In all scenarios the main source of
315 annual changes in carbon stocks comes from loss of SOC in organic soils rather than changes in carbon
316 stocks stored in biomass.

317

318 *Valuation of predicted GHG emissions for agriculture*

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

324

325 [Insert table 6 around here]

326

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

334 Figure 4 represents the predicted annual and cumulative costs of the net flow of UK agricultural GHG
335 emissions for the UKCIP high emissions scenario based on the DECC carbon price function. The net
336 emission intensity of GHGs per area of agricultural land is predicted to decline in England, Wales and
337 Northern Ireland after 2040 (Figure 4(a)) implying an increase in the climate regulatory services.

338 Extending the time horizon to 2060 changes results significantly. The costs of emissions (global dis-
339 service) increase sharply until 2060 (Figure 4(b)). Agricultural GHG costs are predicted to reach
340 £1000/ha in Northern Ireland by 2060 and around £800/ha in both Scotland and Wales. In England
341 emission costs increase from around in £100/ha in 2004 to around £480/ha in 2060. The accumulated
342 total costs of GHG emissions from agriculture between 2004 and 2060 are around £140 billion for
343 England, £24 billion for Northern Ireland, £127 billion for Scotland and £30 billion for Wales(Figure
344 4(d)). Therefore, even the sharp falls in GHG emissions in England may be insufficient to offset the
345 increased cost of carbon imposed on UK agriculture.

346

347 [Insert Figure 4 around here]

348

349 Table 7 presents a disaggregated regional analysis of the predicted annual per hectare cost of agricultural
350 GHG emissions based on the DECC price function for the two UKCIP emissions scenarios. Here the
351 figures in brackets represent the percentage change in carbon costs that are due to climate induced land
352 use change. As such the bracketed values indicate the expected impact on the cost of agricultural GHG
353 emissions in the UK solely due to the land use adjustments induced by global climate change. For
354 instance, in the low emissions scenario, by 2060 the climate induced land use change in south east
355 England is predicted to reduce the average cost of GHG emissions by £257ha⁻¹yr⁻¹ to a net impact of
356 £364 ha⁻¹yr⁻¹ compared to the expected cost of emissions if such land use response did not occur (£621
357 ha⁻¹yr⁻¹). The analysis therefore shows the impact of climate change on GHG emissions in UK
358 agriculture by region, controlling for land use change adjustments that would take place in response to
359 exogenous changes in climate. Note that technical change and agricultural commodity are held constant
360 in this analysis and changes in these variables are likely to induce variations from our predictions.

361

362 [Insert Table 7 around here]

363

364 Table 7 also indicates the inability of even large regional reductions in agricultural emissions to offset
365 rising per unit carbon cost in the UK based on DECC price function. For example, while the east of
366 England is predicted to see a significant(68%) physical reduction in annual GHG emissions between
367 2004 and 2060 (under the high emission scenario), the predicted per hectare cost of emissions will still
368 more than double over that time period due to rising carbon prices. The situation in regions with
369 predicted increases in GHG emissions is potentially even more problematic with carbon costs in
370 Scotland under the high emissions scenario climbing from £100 per hectare in 2004 to almost £800 per
371 hectare in 2060.

372 **Conclusions**

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

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

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

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

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533 **Figures**

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

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

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

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

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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 ₂ e/ha/yr)	N ₂ O emissions from inorganic fertilizer applications (tCO ₂ e/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 ₂ e/head/yr)	Emissions from manure deposited directly onto grasslands (tCO ₂ e/head/yr)	Emissions from manure used as fertilizer (tCO ₂ e/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 tCO₂e/yr)

Year	emissions from manures and enteric fermentation	emissions from agricultural activities (including N ₂ O 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 ₂ e)				
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).

Region	Baseline 2004 (£/ha/yr)	UKCIP low emissions scenario			UKCIP high emissions scenario		
		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.