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Potential effects of future land-use change on regional carbon stocks in the UK

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ABSTRACT

In order to explore the impact of land-use change on carbon (C) stocks in South West England, three scenarios were explored based on current UK national- and regional-scale policies and plans. The scenarios assessed were: (i) Rebuilding Biodiversity (RB), involving habitat restoration of 824,244 ha of strategic nature areas; (ii) Forest Strategy (FS), involving establishment of 16,000 ha of new woodlands; and (iii) Biomass Strategy (BS), involving conversion of 65,513 ha of arable land into bioenergy crops. It was assumed that each of these targets would be implemented by the year 2020, with carbon build-up times of 100, 100 and 30 years, respectively. Estimates of C-stock changes were produced by compiling vegetation and soil organic C-density data for 11 land-use types from a systematic literature review. Results indicated that FS would lead to the highest yearly potential carbon sequestration (up to 3.63 Mg C ha^{-1} yr^{-1}). However, the total C-stocks would be the highest under RB (up to 20% increase), owing to the greater area of pastures and arable land being converted into broadleaved forest when compared to FS. BS would have the least effect on C (C-stock increase of up to 0.3% and up to 0.41 Mg C ha^{-1} yr^{-1} sequestered). The spatially explicit analytical approach adopted here provides an indication of which land-use changes would contribute most to C-sequestration within the South West region, and could contribute to achieving national emission reduction targets post-2012.

1. Introduction

Land-use, land-use change and forestry (LULUCF) contribute to ongoing anthropogenic climate change (Meyer and Turner, 1992; Dale, 1997; Watson et al., 2000; McGuire et al., 2001; Achard et al., 2002; Houghton, 2003), and have consequently received increasing research attention over the last decade (White et al., 2000; Bondeau et al., 2007; Muller et al., 2007; Rokityanskiy et al., 2007; Running, 2008; Smith, 2008; Strassmann et al., 2008; van Minnen et al., 2008; Zomer et al., 2008). LULUCF is one of the five sources of greenhouse gases (GHGs) included in the United Nations Framework Convention on Climate Change (UNFCC) (UNFCCC, 1992), and impact global GHGs emissions, biodiversity and land quality (Cowie et al., 2007). However, LULUCF can also make a significant contribution to the reduction of GHGs, by increasing the carbon storage of terrestrial ecosystems (carbon sequestration), by conserving existing carbon stocks (e.g. by avoiding deforestation or land degradation), and by providing renewable energy (biomass production) (Bloomfield and Pearson, 2000; Schlamadinger et al., 2007; Andersson et al., 2009). Such LULUCF activities are expected to provide a significant and cost-effective way by which atmospheric CO_2 concentration can be reduced, at least in the short- to medium-term (Lal, 2003; Pacala and Socolow, 2004; Nabuurs et al., 2007). They can also assist countries in meeting part of their emissions reduction

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targets that are being proposed for the years after the Kyoto Protocol's first compliance period (2008–2012) (Gainza-Carmenates et al., 2010). Furthermore, mitigation-driven LULUCF activities could have positive effects on the provision of other ecosystem services (Schröter et al., 2005).

In Europe, the future role of LULUCF in the overall carbon balance has been assessed by Schulp et al. (2008) and Zaehle et al. (2007). Both of these studies analysed four land-use change scenarios and concluded that a land-use change from arable cropland to forest (managed or naturally regrowing) leads to an increased carbon sequestration rate, the magnitude of which is influenced by the extent of the area forested. However, a high degree of uncertainty is associated with the carbon estimates obtained, indicating the need for further improvements in spatially explicit data relating to carbon sequestration/emission rates (Mg C ha^{-1} yr^{-1}) for different land-uses.

The effects of mitigation-driven LULUCF activities are expected to be regionally unique, as changes in carbon stocks depend on many regional factors including suitability for different land uses, and the effectiveness of policy for carbon sequestration (Freibauer et al., 2004; Nabuurs et al., 2007). Detailed regional-level analyses are therefore needed to provide accurate estimates of LULUCF offset potentials, in order to help achieve the GHGs target reduction under a post-2012 climate agreement. Nevertheless within Europe, relatively few spatially explicit studies have been undertaken to date on the potential effects of land-use change on carbon stocks (Bolliger et al., 2008; Tappeiner et al., 2008).

The aim of this study was to estimate the extent and spatial changes of carbon stocks under three realistic scenarios of land-use change compared to the current land-use situation at the regional scale of the South West of England (study area: 24,180 km^2; grid cell: 1 ha). Estimates of carbon stock changes were produced by compiling carbon density data for 11 different land-use types, compiled from a literature review. This study focused on landscape-scale changes in the carbon stocks of both vegetation and soils in relation to current land-use (2000) and scenarios of future land-uses (implemented by 2020). The three scenarios reflect different regional strategies to contribute to the delivery of national governmental policy agendas relating to climate change, the natural environment, quality of life and economic development.

2. Methods

2.1. Study area

The South West is the largest of the English regions, covering almost 24,200 km^2 between longitude 1°29′ and 6°22′ W and latitude 49°52′ and 52°06′ N. Annual mean temperature and rainfall for 1971–2000 varies between 7–12 °C and 600–2600 mm (British Met Office <http://www.metoffice.gov.uk>). Much of the landscape consists of plains and low-lying hills, the highest elevations reaching 621 m on Dartmoor. The South West England is characterised by a large variety of land-use types, many of which are common across Europe. It contains almost 80% of the land-cover/land-use classes recorded by the pan-European project Corine Land Cover 2000 Level 3 (CLC2000) (Nunes de Lima, 2005). According to CLC2000, 80% of the entire South West area is represented by agricultural areas, 11% by forest and semi-natural areas, 7% by artificial surfaces and the remaining 2% is covered by wetlands and water bodies.

2.2. Carbon stocks for the current land-use situation

Vegetation and soil carbon stocks were calculated separately for each of 11 land-use types in the South West England. Current land-use types and their areas were extracted for the South West region using the 100 m spatial resolution CLC2000 rasterized map (version 9/2007; <http://dataservice.eea.europa.eu/dataservice>) with the aim of identifying an approach with European applicability. Eleven land-use types derived from CLC2000 level 3 classes were considered for this study: (i) broadleaved forest; (ii) complex cultivation patterns, fruit trees and berry plantations, land principally occupied by agriculture, with significant areas of natural vegetation and transitional woodland-shrub; (iii) coniferous forest, (iv) green urban areas – sport and leisure facilities; (v) inland and salt marshes; (vi) mixed forest; (vii) moors–heathland; (viii) natural grasslands–pastures; (ix) non-irrigated arable land; (x) bioenergy crops; and (xi) peat bogs (Table 1). In line with other carbon assessment studies (i.e. Milne and Brown, 1997; Eaton et al., 2008), the following CLC2000 classes were assumed to have zero carbon and therefore were not considered for carbon accounting: continuous urban fabric, discontinuous urban fabric, industrial or commercial units, road and rail networks and associated land, port areas, airports, mineral extraction sites, dump sites, construction sites, beaches, dunes, sands, bare rocks, sparsely vegetated areas, intertidal flats, water courses, water bodies and coastal lagoons.

The vegetation carbon (VC) and the soil organic carbon (SOC) densities for each land-use type were estimated in Mg ha^{-1} using values derived from a systematic review of the scientific literature. Relevant publications were identified through literature searches of Scopus <http://www.scopus.com> and ISI Web of Knowledge <www.isiknowledge.com> using the search terms 'South West England' and 'land-use' or 'land cover change' and/or the name of each of the 11 land-use types, 'vegetation carbon stock' or 'soil carbon stock', 'storage' or 'sequestration'. Literature searches were incrementally extended from the South West England to the rest of England, UK, Europe and worldwide, until five carbon values were obtained for each land-use type (Table 1). Publications were preferentially selected that referred to data collected in 2000 ± 5 years to be consistent with the CLC2000 data used, and that referred to the organic soil contained in the top 30 cm of soil in line with the IPCC guidance (Nabuurs et al., 2003). Carbon values were adjusted in cases where VC data were collected five or more years before 2000 or SOC data were calculated for a soil deeper than 40 cm on the basis of the literature compiled; when no indication on the soil depth was available this was assumed to be 30 cm (see Appendices A and B). When carbon densities were expressed in dry matter, a carbon fraction of 0.50 g VC g^{-1} dry matter was assumed in line with the IPCC guidance in the case of VC (Nabuurs et al., 2003), and as estimated by Kahle et al. (2001) and Bernal and Mitsch (2008) in the case of SOC. Detailed information on how each of the 110 carbon values has been

Table 1 – Vegetation and soil carbon stock (Mg C ha^{-1}) for the 11 land-use types considered in this study devised from Corine Land Cover 2000 (CLC2000) classes in the South West of England. Carbon density values have been calculated on a basis of 50 studies undertaken in South West England (SW), England (E), United Kingdom (UK), Europe (EU), and worldwide (W). 1 = broadleaved forest; 2 = complex cultivation patterns, fruit trees and berry plantations; land principally occupied by agriculture, with significant areas of natural vegetation; transitional woodland-shrub; 3 = coniferous forest; 4 = green urban areas, sport and leisure facilities; 5 = inland and salt marshes; 6 = mixed forest; 7 = moors and heathland; 8 = natural grasslands; pastures; 9 = non-irrigated arable land; 10 = bioenergy crops; and 11 = peat bogs.

Land-use type	Vegetation carbon stock (MgC ha^{-1})			References[a]	Soil carbon stock (MgC ha^{-1})			References[a]
	$\bar{X}$	X_{MIN}	X_{MAX}		$\bar{X}$	X_{MIN}	X_{MAX}	
1	111	57.4	208	7[UK], 24[UK], 32[UK], 36[E], 38[E]	162	70.5	335	3[SW], 6[E], 30[W], 36[E], 38[E]
2	14.7	2.00	36.7	15[W], 17[W], 22[EU], 32[UK], 36[E]	88.4	37.5	120	6[E], 14[EU], 20[UK], 38[E], 45[W]
3	59.1	26.7	95.8	7[UK], 13[UK], 24[UK], 32[UK], 33[SW]	107	81.9	175	3[SW], 6[E], 12[UK], 13[UK], 30[W]
4	8.32	2.00	25.1	2[UK], 8[UK], 34[W], 46[E], 49[E]	91.3	40.0	142	6[E], 14[EU], 21[UK], 28[EU], 31[EU], 39[E]
5	8.44	1.00	15.0	5[EU], 32[UK], 45[W], 47[EU], 50[W]	143	37.4	235	1[EU], 4[W], 6[E], 14[EU], 45[W]
6	78.0	47.5	139.0	7[UK], 17[W], 24[UK], 30[W], 32[UK]	124	85.6	179	3[SW], 6[E], 26[W], 30[W], 45[W]
7	7.11	2.00	17.5	2[UK], 9[SW], 16[E], 27[EU], 37[UK]	103	50.7	196	6[E], 10[SW], 16[E], 20[UK], 27[EU], 30[W]
8	3.10	1.00	6.98	2[UK], 19[E], 30[W], 32[UK], 45[W]	121	72.0	204	3[SW], 6[E], 21[UK], 38[E], 45[W]
9	2.36	1.00	4.64	2[UK], 32[UK], 40[W], 45[W], 50[W]	63.9	27.5	88.2	6[E], 21[UK], 38[E], 43[UK], 44[EU]
10	2.90	1.56	4.47	11[EU], 23[EU], 29[E], 35[EU], 41[UK]	74.6	69.8	80.2	11[EU], 18[E], 23[EU], 25[E], 42[EU]
11	7.15	1.57	20.0	2[UK], 17[W], 32[UK], 45[W], 48[E]	576	133	1170	14[EU], 21[UK], 26[W], 32[UK], 45[W]

[a] 1, Álvarez-Rogel et al. (2007); 2, Adger and Subak (1996); 3, Bateman and Lovett (2000); 4, Bernal and Mitsch (2008); 5, Bouchard and Lefeuvre (2000); 6, Bradley et al. (2005); 7, Cannell and Milne (1995); 8, Cannell et al. (1999); 9, Chapman (1967); 10, Chapman (1970); 11, Clifton-Brown et al. (2007); 12, Conen et al. (2005); 13, Dewar and Cannell (1992); 14, Eaton et al. (2008); 15, Egunjobi (1971); 16, Garnett et al. (2001); 17, Gibbs (2006); 18, Grogan and Matthews (2002); 19, Hector et al. (1999); 20, Howard et al. (1995a); 21, Howard et al. (1995b); 22, Janssens et al. (2003); 23, Kahle et al. (2001); 24, Karjalainen et al. (2003); 25, King et al. (2004); 26, Lal (2004); 27, Larsen et al. (2007); 28, Lorenz and Kandeler (2005); 29, Lovett et al. (2009); 30, McGuire et al. (1997); 31, Mestdagh et al. (2005); 32, Milne and Brown (1997); 33, Milne et al. (1998); 34, Nowak and Crane (2002); 35, Ovando and Caparrós (2009); 36, Patenaude et al. (2003); 37, Penuelas et al. (2007); 38, Poulton et al. (2003); 39, Rawlins et al. (2008); 40, Reiners (1973); 41, Rowe et al. (2009); 42, Smith and Falloon (2005); 43, Smith et al. (2000a); 44, Smith et al. (2000b); 45, Taylor and Lloyd (1992); 46, Tratalos et al. (2007); 47, Van Ryckegem et al. (2006); 48, Ward et al. (2007); 49, Whitford et al. (2001); and 50, Whittaker (1977). Values are mean ($\bar{X}$), minimum (X_{MIN}) and maximum (X_{MAX}).

calculated can be found in the on-line supplementary material (Appendices A and B).

Mean, minimum and maximum carbon densities for each land-use were calculated from the five VC and the five SOC values extracted from the literature review. To determine the total mean/minimum/maximum carbon stocks for the South West region under the current situation, each of the 11 land-use type was assigned a mean/minimum/maximum carbon density (Mg ha^{-1}). The carbon densities were then converted into total carbon by multiplying them by the area covered by each land-use type. The spatial distribution of the carbon stock was mapped by assigning to each grid cell of the CLC2000 map the mean carbon density for the land-use type attributed to the grid cell.

2.3. *Scenarios of future land-use change*

We developed three spatially explicit scenarios of future land-use change based on different national and regional strategies: (i) South West England 'Rebuilding Biodiversity' strategy (RB), (ii) national forest strategy (FS), and (iii) national biomass strategy (BS). It was assumed that each of the policy targets would be implemented by 2020, with no additional changes in land use taking place thereafter. However, the impacts of land use changes on carbon sequestration are likely to occur over many years, as vegetation develops. The three scenarios represent static projections of land-use change, therefore specific build-up times for a land-use to become carbon 'saturated' were not explicitly determined. Instead, carbon build-up times were assumed to be 30 years for the BS scenario and 100 years for RB and FS scenarios, to account for the difference between a typical bioenergy crop cycle and forest maturation.

The RB scenario is based on an innovative approach for the South West region that has recently been developed by local conservation organisations. This aims to ensure the long-term conservation of all priority wildlife habitats in the South West England, by defining ecologically functional fragments at the landscape scale (referred to as strategic nature areas, SNAs) where habitat restoration should be delivered in the future. The SNAs and their land-use type have been identified in a map, called 'Nature Map', which identifies the location of biodiversity restoration actions and is designed to inform strategies for sustainable development (South West Wildlife Trusts, 2005; Oxford, 2007). The Nature Map was downloaded (<http://www.biodiversitysouthwest.org.uk/nm_dwd.html>) and rasterized at 100 m resolution to make it compatible with CLC2000.

The Nature Map habitat types were reclassified using the land-use classification adopted in this study (Table 2). The 100 m raster Nature Map and CLCL2000 were combined such that all meaningful land-use conversions prioritised with Nature Map were applied. The output map (i.e. RB map) thus contained CLC2000 land-cover for all grid cells outside Nature Map priority area boundaries and for those areas inside the Nature Map boundaries for which land-cover conversions are null or would be unlikely (e.g. conversion of peat bogs into grasslands or heathland). All other grid cells subjected to a

Table 2 – Land-use types equivalence table between the land-use classification used in the Nature Map (South West Wildlife Trusts, 2005; Oxford, 2007) and the classification used in this study (based on CLC2000).

Land-use type nature map	Land-use type this study
Woodland	Broadleaved forest
Coastal and floodplain grazing marsh	Inland and salt marshes
Lowland heath Upland heath	Moors–heathland
Chalk downland Limestone grassland Neutral grassland Purple moor grass and rush pasture	Natural grasslands–pastures
Coastal habitats Standing open water	Not considered in this study

land-use change (totalling 824,244 ha) were given a new land-use type in accordance with Nature Map conservation priorities. Each of the 11 land-use types was assigned a mean/minimum/maximum carbon density (Mg ha^{-1}), calculated as in the current land-use situation, and the carbon densities were converted into total carbon (Mg) by multiplying them by the area covered by each land-use type. The spatial distribution of the carbon stock was mapped by assigning to each grid cell of the RB map the mean carbon density for the land-use type attributed to the grid cell.

A specific timeframe for the delivery of the RB scenario is not reported in the main technical document (i.e. South West Wildlife Trusts, 2005). However, policy ENV4 (nature conservation) of the draft regional spatial strategy for the South West 2006–2026 requires all local authorities to implement the RB scenario as a means of implementing the UK Biodiversity Action Plan (South West Regional Assembly, 2006).

The FS scenario is based on the strategy for England's tree, woods and forests (ETWF) which aims to create, expand and maintain a network of sustainably managed woodlands, both to protect and enhance these environmental resources and to promote the development of new or improved markets for ecosystem services, including carbon sequestration (DEFRA, 2007a). In the ETWF delivery plan for 2008–2012, the Forestry Commission (FC) and Natural England (NE) plan to plant trees and create new woodlands prioritising the buffering and extension of ancient and semi-natural woodland to a national target area of 80,000 ha by 2020 (Forestry Commission and Natural England, 2007), equivalent to 14,813 ha for the South West region. The South West Biodiversity Partnership also aims to extend and buffer existing large areas of ancient woodland to a similar target area equal to 16,800 ha by 2020 (Woodland and Forestry Framework Steering Group, 2005; BRERC, 2006). In this study we used a target value of 16,000 ha of new broadleaved woodlands, close to average target value of the FC and NE, and the South West Biodiversity Partnership ($\bar{X} = 15,806$ ha).

In order to simulate the FS scenario, the boundaries of Ancient Woodlands (AW) in England were downloaded (in vector format) from the NE website <http://www.gis.naturalengland.org.uk> and the AW areas were extended by creating 100 m buffers around them. By overlaying this on the CLC200 map, the buffering was only allowed on selected land-use types that are considered appropriate for reafforestation according to the RB strategy, including pastures, arable land and small percentages of moors–heathland and natural grasslands (3.52% and 1.75% of their current area, respectively) (South West Wildlife Trusts, 2005). This identified a potential of 67,248 ha of new broadleaved woodlands from the buffered AW polygons. A random selection of the polygons was performed to reach the target value of 16,000 ha using Hawth's Analysis Tools © 2002–2007 v3.27. The random selection was repeated four times. To determine the total mean/minimum/maximum carbon stocks for the South West region under the FS scenario, the areas of the 11 land-use types (in hectares) were re-calculated from the current land-use situation for all the four repetitions of the AW expansion and then multiplied by the mean/minimum/maximum carbon densities of each land-use type (Mg ha^{-1}). The spatial distribution of the carbon stock was mapped using the same approach adopted in the RB scenario.

The BS scenario is based on the national biomass strategy that acknowledges the importance of fuels sourced from biomass in tackling climate change and in meeting the EU target of 20% renewable energy by 2020 (EU Biofuels Directive 2003/30/EC), to which the UK Government signed up in 2008 (DEFRA, 2007b; BERR, 2008). Current assessments indicate that 30% of that renewable energy would come from bioenergy, mainly in the form of short rotation coppice (SRC) and *Miscanthus* cultivation. This has been reflected in the SW region, where the Regional Economic Strategy (RES) and the Draft Regional Spatial Strategy (DRSS) provides targets and policy guidance to increase renewable energy supply (South West Regional Assembly, 2006). The Department for Environment, Food and Rural Affairs (DEFRA) aims to increase the amount of perennial energy crops produced in the UK to meet market demands, with the potential to use up to a further 350,000 ha across the UK by 2020 (DEFRA, 2007b), equivalent to 66,194 ha for the South West region from the period 2000–2020.

Since the policy documents do not specify between SRC and *Miscanthus* cultivation, and the average carbon values of these bioenergy crops are very close (in this study 79.3 Mg C ha^{-1} in SRC and 77.5 Mg C ha^{-1} in *Miscanthus*) we considered them as a single land-use type. To determine the total carbon stocks for the South West region under the BS scenario we created a map of suitability for bioenergy by selecting the arable land areas on Grades 3 (good–moderate quality) and 4 (poor quality) of the national Agricultural Land Classification (ALC) areas in line with Lovett et al. (2009), which indicated that Grades 3 and 4 areas the most suitable for *Miscanthus*. The ALC for England was downloaded form the Multi-Agency Geographic Information for the Countryside (MAGIC) website <http://www.magic.gov.uk>. The suitability map indicated that a potential 434,284 ha of arable land in the South West England could be converted into *Miscanthus*. A constraint was added to this map which eliminated 40,003 ha considered 'unsuitable' for SRC according to the SRC yield map produced by DEFRA for the South West region (DEFRA, 2010b). To map the spatial distribution

Table 3 – Look-up table used to calculate gains and losses of C stocks (Mg ha^{-1}) in the South West of England. See Table 1 for detail on the 11 land-use types considered.

From	To										
	1	2	3	4	5	6	7	8	9	10	11
1	0.00	−169	−107	−173	−121	−71	−162	−149	−206	−195	310
2	169	0.00	62.6	−3.4	48.1	98.7	7.0	20.9	−36.7	−25.5	480
3	107	−62.6	0.00	−66.0	−14.6	36.1	−55.6	−41.8	−99.4	−88.1	417
4	173	3.40	66.0	0.00	51.5	102.1	10.4	24.3	−33.3	−22.1	483
5	121	−48.1	14.6	−51.5	0.00	50.6	−41.1	−27.2	−84.8	−73.6	432
6	71	−98.7	−36.1	−102.1	−50.6	0.00	−91.7	−77.8	−135	−124	381
7	162	−7.01	55.6	−10.4	41.1	91.7	0.00	13.8	−43.8	−32.5	473
8	149	−20.9	41.8	−24.3	27.2	77.8	−13.8	0.00	−57.6	−46.4	459
9	206	36.7	99.4	33.3	84.8	135	43.8	57.6	0.00	11.2	516
10	195	25.5	88.1	22.1	73.6	124.2	32.5	46.4	−11.2	0.00	505
11	−310	−480	−417	−483	−432	−381	−473	−459	−516	−505	0.00

of the carbon stock under the BS scenario, land parcels from the suitability map were selected at random aiming to achieve a total area as close as possible to the target value of 66,194 ha. This resulted in a new map (i.e. BS map) with 65,513 ha of bioenergy crops. CLC2000 map classes 9 and 10 (non-irrigated arable land and bioenergy crops) were re-calculated from the current land-use situation and then multiplied by the mean/minimum/maximum carbon densities of land-use types 9 and 10 (Mg ha^{-1}). The spatial distribution of the carbon stock was mapped using the same approach adopted in the RB scenario.

Carbon net gains and losses of the three scenarios versus the current situation were calculated as the difference between the mean carbon stocks under each scenario and the current situation (Table 3). To facilitate comparison between the three scenarios the potential C sequestration of each scenario in Mg C ha^{-1} yr^{-1} and Mg C ha^{-1} by 2050 were also calculated.

3. Limitations and simplifications

First, we assumed that none of the land-use types are either gaining or losing carbon over time. The only changes in carbon stocks that we considered are the result of changes from one land-use type to another. Therefore, any grid cell that did not change its land-use type would have zero carbon sequestration over time. In reality, many land-use types that are undergoing natural succession can continue to accumulate carbon for a very long time (e.g. Luyssaert et al., 2008). Second, we did not account for any of the GHGs emitted during the change from one land-use type to another. Third, the GHGs emissions from agricultural activities were not included, and neither was any anthropogenic deposition of GHGs (i.e. CH_4, N_2O). Fourth, for the bioenergy land-use type we did not account for the carbon savings arising from the reduced use of fossil fuels. In addition, we did not address the impact of climate change on carbon sequestration of the land-use types considered in this study. Also, we did not consider the potential impacts of displaced food production from the conversion of arable/pasture to less productive agricultural habitats. It is important to consider these limitations when interpreting the results obtained.

4. Data analyses

Statistical analyses were performed using SPSS 16.0 for Windows (© 1989–2007, SPSS Inc., USA). Descriptive statistics were used to calculate the mean/minimum/maximum of the carbon values. A Mann–Whitney test was used to compare VC and SOC values. The spatial distribution of the carbon stocks was mapped using ArcGIS 9.2 (© 1999–2006 ESRI Inc., California, USA).

5. Results

5.1. *Current carbon stocks in the South West*

The overall C stock for the South West of England in 2000 is estimated on average at 263 Tg (10^{12} g) (Table 4 and Fig. 1), with values ranging from 137 to 442 Tg when using the minimum and maximum carbon densities reported in the literature review, respectively. Vegetation carbon densities are on average the largest for broadleaved forest, and the lowest for non-irrigated arable land, whereas soils carbon (SOC) densities are on average the largest for peat bogs and the lowest for non-irrigated arable land. When VC and SOC are considered together, then the peat bog land-use type contains the largest density of carbon, followed by broadleaved forest; whereas the non-irrigated arable land-use is estimated to have the lowest carbon value (Table 1). SOC significantly differed from VC ($Z = -7.52$, $P < 0.001$; Mann–Whitney test for all carbon densities considered together) and was on average 5.5 times greater than VC($\bar{X} = 151$ Mg C ha^{-1} in SOC and $\bar{X} = 27.5$ Mg C ha^{-1} in VC).

5.2. *Effects of land-use change scenarios on carbon budget and spatial distribution of gains and losses*

Under the RB scenario, the overall C stock for the South West of England is estimated on average at 300 Tg (10^{12} g) (Table 4 and Fig. 2), with values ranging from 150 to 529 Tg when using the minimum and maximum carbon densities reported in the literature review, respectively. This equals to a potential carbon sequestration between 0.16 and 1.06 Mg C ha^{-1} yr^{-1}. An average C stock increase of 14% (37.4 Tg) would be expected

Table 4 – Land-use types areas (hectares), vegetation carbon (VC), soil organic carbon (SOC) stocks (Mg C) and potential carbon sequestration (Mg C ha^{-1} yr^{-1}) in the South West of England for the current situation (2000) and under three scenarios of land-use change. Values are based on mean VC and SOC for the 11 land-use types considered in this study (see Table 1). FS scenario values are mean ($\bar{X}$) and standard errors (S.E.) based on four repetitions. Potential carbon sequestration values are mean ($\bar{X}$), minimum (X_{MIN}) and maximum (X_{MAX}). See Sections 2.2 and 2.3 for more details on the scenarios considered.

CLC2000 types	Current situation	Scenario RB	Scenario FS	Scenario BS
	$\bar{X}$	$\bar{X}$	$\bar{X}$ (±S.E.)	$\bar{X}$
1				
Area	117 939	321 618	133 942 (±2)	117 939
VC + SOC	32 131 301	87 621 608	36 491 090 (±30)	32 131 301
SOC	19 051 866	51 954 172	21 636 950 (±23)	19 051 866
2				
Area	317 798	231 138	317 798	317 798
VC + SOC	32 745 906	23 816 460	32 745 906	32 745 906
SOC	28 086 987	20 427 976	28 086 987	28 086 987
3				
Area	38 486	10 978	38 486	38 486
VC + SOC	6 376 360	1 818 835	6 376 360	6 376 360
SOC	4 101 838	1 170 035	4 101 838	4 101 838
4				
Area	26 381	17 934	26 381	26 381
VC + SOC	2 628 497	1 786 872	2 628 497	2 628 497
SOC	2 409 113	1 637 733	2 409 113	2 409 113
5				
Area	6 228	71 966	6 228	6 228
VC + SOC	941 200	10 875 790	941 200	941 200
SOC	888 611	10 268 109	888 611	888 611
6				
Area	9 386	1 303	9 386	9 386
VC + SOC	1 893 532	262 867	1 893 532	1 893 532
SOC	1 161 424	161 233	1 161 424	1 161 424
7				
Area	26 133	168 838	26 064 (±6)	26 133
VC + SOC	2 876 041	18 581 297	2 868 447 (±59)	2 876 041
SOC	2 690 131	17 380 184	2 683 028 (±57)	2 690 131
8				
Area[a]	1 088 514	931 366	1 076 947 (±11)	1 088 514
Area[b]	70 221	68 994	70 006 (±8)	70 221
VC + SOC	143 569 584	123 946 605	142 109 802 (±118)	143 569 584
SOC	139 975 188	120 843 488	138 551 953 (±117)	139 975 188
9				
Area	533 662	410 613	529 510 (±12)	468 149
VC + SOC	35 383 925	27 225 284	35 108 631 (±94)	31 040 151
SOC	34 122 348	26 254 595	33 856 869 (±92)	29 933 447
10				
Area	0	0	0	65 513
VC + SOC	0	0	0	5 080 140
SOC	0	0	0	4 889 890
11				
Area	7 308	7 308	7 308	7 308
VC + SOC	4 258 766	4 258 766	4 258 766	4 258 766
SOC	4 206 485	4 206 485	4 206 485	4 206 485
Overall VC + SOC	262 805 113	300 194 384	265 422 232 (±86)	263 541 480
Overall SOC	236 693 991	254 304 010	237 583 258 (±85)	237 394 980
C sequestration $\bar{X}$ (X_{MIN}, X_{MAX})		0.45 (0.16–1.06)	1.64 (0.67–3.63)	0.37 (−0.14–0.41)

[a] Pastures.
[b] Natural grasslands.

after an estimated build-up time of 100 years. 7.5% (19.8 Tg) would be achieved by carbon sequestration in vegetation and 6.7% (17.6 Tg) by carbon sequestration in soil (Fig. 3). Broad-leaved forest and moors–heathland would be the land-use types that contribute most to the average C stocks increase (+23 Tg in VC and +33 Tg in SOC for broadleaved forest; and +1.0 Tg in VC and +15 Tg for moors–heathland), owing to an expansion of their area of 203,679 and 142,705 ha, respectively; whereas natural grasslands–pastures would decrease their average C stocks (−0.5 Tg in VC and −19 Tg in SOC) owing to a

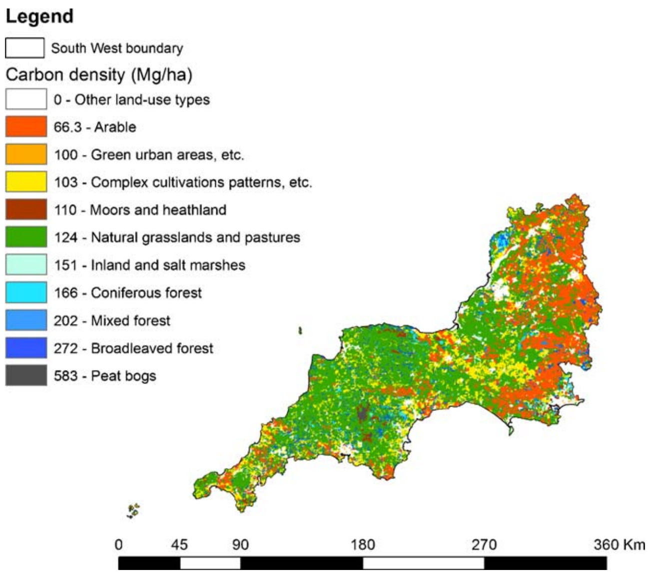

Fig. 1 – Current spatial distribution of carbon stocks (vegetation and soil carbon) (Mg ha^{-1}) for the 11 land-use types considered in this study devised from the Corine Land Cover 2000 (CLC2000) classes in the South West of England. Carbon density values have been calculated on a basis of 50 publications. See Section 2.2 for more details.

reduction of their areas of −158,375 ha. New broadleaved forests would be established on pastures (49%), arable and complex cultivation patterns (39%), coniferous and mixed forests (9%), green urban areas (2%), moors–heathland and natural grasslands (1%).

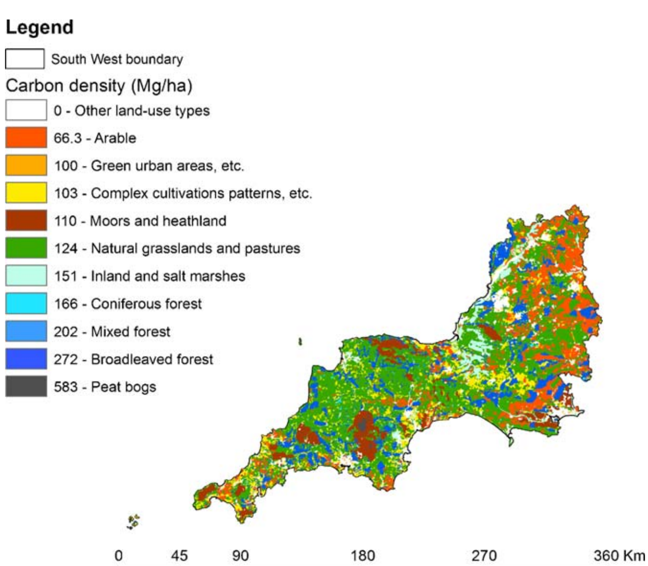

Fig. 2 – Spatial distribution of carbon stocks (vegetation and soil carbon) (Mg ha^{-1}) under the Rebuilding Biodiversity (RB) scenario for the 11 land-use types considered in this study in the South West of England. See Section 2.3 for a description of the RB scenario and details on how the RB map has been produced.

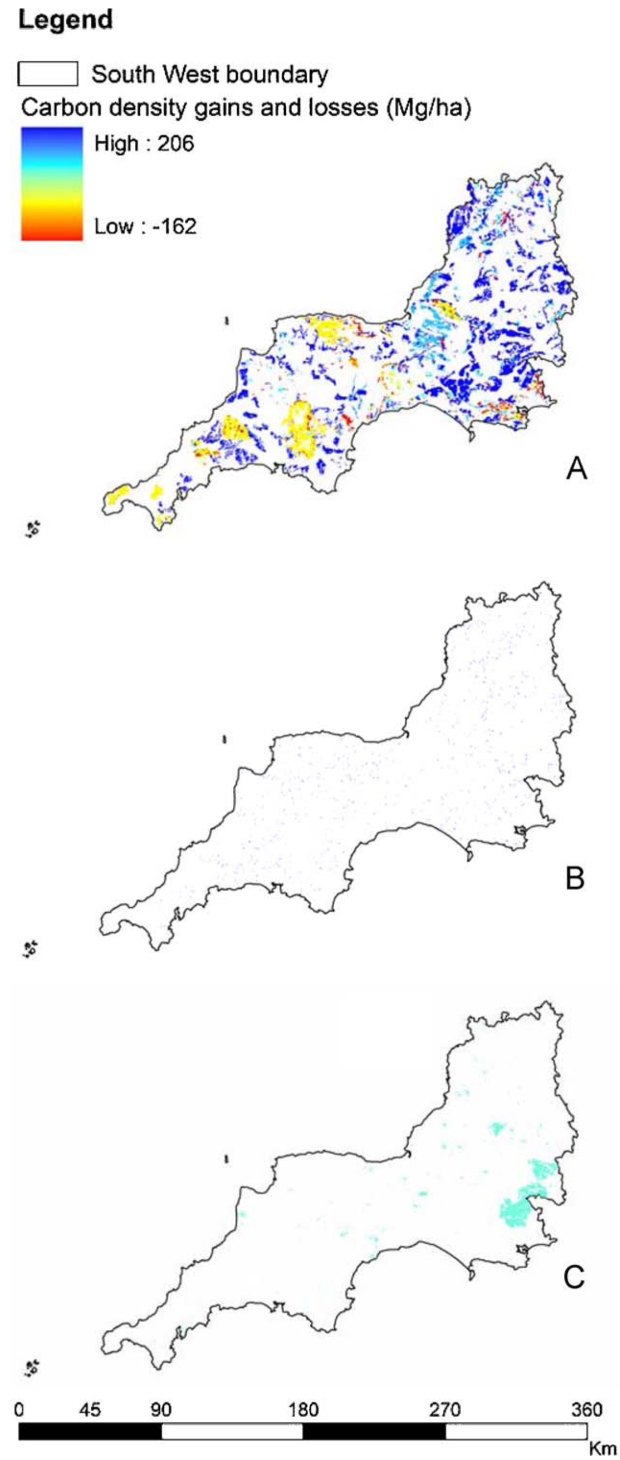

Fig. 3 – Gains and losses of C stocks (Mg ha^{-1}) of the three scenarios considered in this study versus the current situation (2000) in the South West of England. Gain and losses were calculated as difference between the spatial distribution of carbon stocks under each scenario and the current situation (see Table 3). (A) Gains and losses under the Rebuilding Biodiversity scenario, (B) gains under the Forest Strategy scenario (for the first woodland expansion repetition) and (C) gains under Biomass Strategy scenario. For scenario description see Section 2.3.

Under the FS scenario the overall C stock for the South West of England is estimated on average at 265 Tg (10^{12} g) (Table 4), with values ranging between 138 and 447 Tg when using the minimum and maximum carbon densities reported in the literature review, respectively. This translates into a potential carbon sequestration varying from 0.67 to 3.63 Mg C ha^{-1} yr^{-1}. The FS scenario resulted in a small average increase of 1.0% in C stocks (2.6 Tg) compared to the situation in 2000 after an estimated build-up time of 100 years. 0.7% (1.7 Tg) would be achieved by carbon sequestration in vegetation and 0.3% (0.9 Tg) by carbon sequestration in soil (Fig. 3). Broadleaved forests would increase their C stocks of +4.4 Tg (+1.8 Tg in VC and +2.6 Tg in SOC) thanks to 16,000 ha of new woodlands; whereas natural grasslands–pastures would decrease their C stocks of −1.5 Tg (−0.04 Tg in VC and −1.46 Tg in SOC) owing to a reduction of their areas of −11,782 ha.

Under the BS scenario the overall C stock for the South West of England is estimated on average at 264 Tg (10^{12} g) (Table 4), with values ranging from 139 to 441 Tg when using the minimum and maximum carbon densities reported in the literature review, respectively. This corresponds to a potential carbon sequestration between −0.14 and 0.41 Mg C ha^{-1} yr^{-1}. The conversion of 65,513 ha of arable land into bioenergy crops results in a very small mean increase of 0.3% in C stocks (0.7 Tg) compared to the situation in 2000 after an estimated build-up time of 30 years. 0.01% (0.04 Tg) would be achieved by carbon sequestration in vegetation and 0.27% (0.70 Tg) by carbon sequestration in soil (Fig. 3).

When the three scenarios are expressed in Mg C ha^{-1} by 2050 (i.e. timeline for a typical bioenergy crop cycle under BS), carbon sequestration is estimated on average at 11.2, 13.6, and 49.1 Mg C ha^{-1} under BS, RB and FS scenarios, respectively.

6. Discussion

In response to the UNFCCC and Kyoto Protocol international agreements, the UK has developed a Climate Change Act that sets out a legal commitment to reduce the net carbon account by at least 80% by 2050 (HM Government, 2008). This national policy commitment has been reflected in regional development strategies, such as that developed by the South West Regional Development Agency (SWRDA), which refers explicitly to the need for transformation towards a low carbon economy and has identified sustainable rural development as a priority in the regional spatial strategy for 2006–2026 (South West Regional Assembly, 2006). The aim of the present investigation was to estimate the size and spatial changes of C stocks of three realistic scenarios of future land-use (implemented by 2020), based on current national- and regional-scale policies and plans, to analyse the opportunities for reducing the net carbon account of the South West region by altering current patterns of land-use. Previous studies have suggested that land-use changes can help reduce CO_2 atmospheric concentration, at least in the near term (e.g. Bloomfield and Pearson, 2000; Cannell, 2002; Lal, 2003; Nabuurs et al., 2007; Schulp et al., 2008), but land-use mitigation capacities for the South West region have previously received very little attention from researchers.

When interpreting the results presented here, it is important to consider the simplifying assumptions made, and the fact that the scenarios differ in terms of the areas over which they envisage change and the time periods over which carbon is likely to be accumulated. However, when the three scenarios are expressed in Mg C ha^{-1} yr^{-1}, the FS scenario would lead to the highest yearly carbon sequestration per hectare (up to 3.63 Mg C ha^{-1} yr^{-1}), followed by the RB and the BS scenarios. Of the land-use types considered in this study, broadleaved forests have the highest C stock, therefore a scenario that focuses entirely on their expansion would always deliver higher total carbon sequestration than any alternative scenario, in cases where scenarios are applied to the same area and length of time. Our analyses suggest that afforestation on former grasslands–pastures, moors–heathland and arable land can sequester considerable C quantities. A recent review (Guo and Gifford, 2002) indicates that on average, the soil C stock increases by between 18% and 53% after land-use changes from agricultural crops to forest plantation and to secondary forest, respectively, whereas planting broadleaved forest into pasture has little effect on soil C stocks. Post and Kwon (2000) report that there is a considerable variation in accumulation rates of soil C stock when forest is established on sites of previous agricultural use, depending on factors such as the physical and biological conditions in the soil, past history of soil organic carbon inputs and physical disturbance, and productivity of the forest. Our analyses also suggest that variation in the SOC value is high for broadleaved forest. However, most of the studies conducted in the UK provide comparable mean C accumulation rates for broadleaved forest, indicating that accumulation rates may be fairly constant (Cannell and Milne, 1995; Milne and Brown, 1997; Post and Kwon, 2000; Poulton et al., 2003; Bradley et al., 2005). Our analyses also suggest that broadleaved forest stores on average 206 Mg C ha^{-1} and 149 Mg C ha^{-1} more than the arable, and the grassland–pasture land-use types, respectively.

The results presented here suggest that when the three scenarios are expressed in total Mg C, the RB scenario would lead to the highest increase of C stocks, with an increase of up to 20% compared to the current land-use situation under an estimated build-up time of 100 years. Of the three scenarios, RB has the greater area of pastures (9.7% of the current area) and arable land (8.1% of the current area) being converted into broadleaved forest, which explains the highest C stocks obtained. The area proposed for new woodlands (i.e. 203,679 ha) is almost 13 times higher than under FS, which highlights the ambitious nature of the RB scenario. The FS scenario would likely have a very limited impact on C stocks compared to the current situation. An increase of up to 1.3% is estimated for the conversion of 16,000 ha of grasslands, pastures, moor and heathland and arable land into broadleaved forest, under an estimated built-up time of 100 years. Although the yearly carbon sequestration per hectare is the highest under FS, the target of 16,000 ha new woodlands by 2020, equal to only 1% of the total grassland, pasture, moor, heathland and arable area, would need to be increased substantially to have an overall significant C sequestration in the South West England. For example, an additional 102,224 ha, 72.3% of which covered by pastures, 26% by arable, 1.3% by natural grassland and 0.4% by moors–heathland, would need to be converted into woodland to reach the same C stock estimated under the RB scenario. This additional area of woodland expansion would require a stronger policy intervention than the one currently proposed under the FS scenario.

The results presented here indicate that the BS scenario would lead to the lowest mean increase in total C stocks under based on an estimated build-up time of 30 years. A mean increase of 0.3% is estimated for the conversion of 65,513 ha of arable land into bioenergy crops compared with the current situation. Our analyses suggest that on average bioenergy crops store only 11 Mg C ha^{-1} more than arable land. Therefore even if the percentage of land converted is relatively high (12% of the arable land in our case), the BS scenario is unlikely to lead to considerable carbon sequestration. Nevertheless, establishment of effectively managed bioenergy crops on former arable land has been identified as the agricultural land-use change with the greatest potential for C mitigation in the UK and across Europe (Smith et al., 2000b,c; Forestry Commission, 2007; Ovando and Caparrós, 2009; Rowe et al., 2009), and approximately 7500 ha of bioenergy crops were established in England between 2001 and 2007 (Lovett et al., 2009). However, it should be noted that our results on carbon sequestration should not be compared directly with the results obtained by Smith et al. (2000b,c), FC (2007), and Ovando and Caparrós (2009), as these studies consider the potential mitigation of GHG emissions that can be derived from fossil fuel substitution, which as noted earlier, was not included in our calculations. In addition, we do not consider here any further changes in land use after 2020, and recognise that UK Government policies, such as the Low Carbon Transition Plan (HM Government, 2009), are already beginning to extend beyond this timeline.

According to the findings of this study, the FS scenario would sequester up to 3.63 Mg C ha^{-1} yr^{-1} by converting current pasture areas and arable land into broadleaved forests. Afforestation is currently included under the Kyoto Protocol (Article 3.3) as a valid means of reducing CO_2 emissions, and LULUCF projects aiming at afforesting grassland, pastures and arable areas in the South West region would potentially be eligible for carbon credits. Some incentives for native woodland establishment are already in place (i.e. the English Woodland Grant Scheme), but a stronger policy intervention to drive land-use changes would be needed to achieve the carbon sequestration potential suggested here under the RB scenario. Rokityanskiy et al. (2007) indicate that carbon sequestration policies such as those promoting afforestation could play a significant contribution within the global range of GHG mitigation options, dependent on the level of carbon prices. This could also help support the income of UK farmers, which has fallen by 6.7% in 2009 and is forecast to continue decreasing across all farm types (DEFRA, 2010a). Although carbon prices vary widely internationally, a current estimate for Europe can be taken from the leading carbon trading marketplace in Europe, namely the European Climate Exchange (ECX), which is currently trading carbon at 13.44 Euros per metric ton (Mg) of CO_2 or €49 per Mg of carbon (as of July 27, 2010). Using an estimate of €49 per Mg of carbon, the market value of carbon storage in the land-use types under the RB scenario would be €1832 million higher than the current situation (€12,877 million), while under the FS and BS scenarios the market value of carbon storage would only exceed the current value by €126 million and €35 million, respectively. This difference reflects variation between the scenarios in terms of the amount and type of land use change envisaged, but provides an indication of the potential carbon storage market value of the same landscape under different land-use type combinations.

Further research is required to fully identify both the costs and benefits associated with the policy actions explored here, to fully quantify the overall net economic impact of the three scenarios. A range of different costs and benefits could potentially be considered, leading to high variation between estimates of economic impact (Bateman et al., 2005; Balmford et al., 2008). Although some attempts have been made to conduct cost–benefit analyses of restoration initiatives (i.e. Naidoo and Ricketts, 2006; Nelson et al., 2009), research in this area is still at a very early stage (Nelson et al., 2008; TEEB, 2009). Detailed information on the potential costs of implementing the scenarios explored here is not currently available, but some indicative costs of establishing new woodland, *Miscanthus* and SRC are 2145€ ha^{-1}, 1849€ ha^{-1} and 2036€ ha^{-1}, respectively (Forestry Commission, 2010; Wales Energy Crops Information Centre, 2010), whereas restoring inland wetlands could cost up to 25,425€ ha^{-1} (TEEB, 2009).

Relatively few spatially explicit studies have been undertaken to date on the potential effects of land-use changes on carbon stocks at the regional scale (Bolliger et al., 2008; Tappeiner et al., 2008). Of three scenarios developed in Switzerland, i.e. (i) business as usual, (ii) full extensification of open-land, and (iii) full reforestation potential, Bolliger et al. (2008) concluded that the largest increase in C stocks is expected under the third scenario, mainly owing to greater C stocks in forest biomass and soils. Tappeiner et al. (2008) analysed the effects of future land-use change on carbon stocks in an Alpine valley of Austria under contrasting scenarios based on stakeholder consultations and on a Markovian model. Although the scenarios and timescales developed by Bolliger et al. (2008) and Tappeiner et al. (2008) differ from those presented here, our findings agree with their conclusions indicating that total carbon sequestration is highest under a scenario involving a significant increase in forest areas, which might be achieved by environmental payments to landowners.

In summary, despite the simplifying assumptions that we made, the spatially explicit analytical approach employed could be of value to land managers and policy makers to identify areas where land-use changes would contribute most to increasing carbon storage. Maps such as those developed here can illustrate the carbon stock values of different land-use types and the potential impacts of altering current patterns of land-use. They can also help to identify priority areas for carbon sequestration, and to direct payments for carbon stocks to land managers. In this way, the approach adopted here could support improved valuation and provision of ecosystem services, and thereby contribute to the sustainable development of rural areas.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.envsci.2010.10.001.

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