Natural England Research Report NERR043

Carbon storage by habitat: Review of the evidence of the impacts of management decisions and condition of carbon stores and sources

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Project details

A summary of the findings covered by this report, as well as Natural England's views on this research, can be found within Natural England Research Information Note RIN043.

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This is a review in a quickly developing field and we could not cover every aspect or include each reference, but we would welcome feedback on the report. Please contact the project manager (details below).

Project manager

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Summary

The aims of this Natural England cross-cutting Evidence project were:

1) To collate information and identify knowledge gaps on carbon stocks (both in vegetation and soils) for important terrestrial, coastal and marine habitats in England.
2) To determine how different management options may impact on sequestration or loss of carbon by habitat.

The most detailed assessment of the soil carbon stock in this country in semi-natural habitats was carried out as part of the Countryside Survey 2007. Therefore, we use here, when possible, the same terminology. The habitats we have considered for this review are:

- Grasslands, including Semi-natural and semi-improved[1] grasslands;
- Dwarf shrub Heath, upland and lowland;
- Wetlands, including Bog, Fen, Marsh and Swamp habitats;
- Woodlands, including Broadleaved, Mixed and Yew woodlands and Coniferous woodlands;
- Arable and horticultural land, including improved grasslands;
- Coastal, including Sand dunes, Saltmarshes, Estuaries; and
- Marine, including Sea grass meadows and macroalgal beds, and Offshore sediments (North Atlantic).

The most important differences that land and marine managers, conservationists and farmers alike, could make by adapting our management practices are:

- Avoid or reduce soil (or coastal substrates) disturbance when managing and even restoring habitats. Consider steady changes to habitats and soils, such as gradual felling, instead of more disturbing approaches, such as clear felling of large areas.
- Reduce the amount of waste or by-products which are burned or sent to landfill from management interventions. This could require developing new market opportunities. For example, try to reuse or compost arisings from heathland management, as well as wood fuel, timber and wood products, for energy production in a low carbon economy; or find use for the hay from semi-natural meadows.
- Reduce the amount of fertiliser from intensively managed land leaching into water courses and coastal and marine habitats. Consider, instead, and where appropriate, using legumes to fix nitrogen, for example, reseeding them with rye-grass.
- Reduce, and where possible reverse, the erosion and degradation of peatlands, including by grip blocking in the uplands and restoration of lowland agricultural peats.
- Consider the conversion of arable to permanent grassland or other semi-natural habitat which requires less soil disturbance.

[1] When published information does not differentiate between grasslands types, including whether they have been improved, the figures are included in the grassland section

The main uncertainties which remain after this review are:

- Much of the existing evidence comes from models at European or global scale. We need to ground-truth these models at smaller scale to be able to see what they mean for field-scale practices.
- This review collated the results of a variety of projects and research objectives. Large uncertainties remain on the extent to which some data is relevant for the English context. Some uncertainty may also have been introduced when transforming the units used to be consistent for this work from a large number of sources.
- It is not possible yet to translate the impact of a particular management decision or climatic forecast into a precise amount of carbon which will be stored or released as a result into the atmosphere or the ocean.

However, this project will help to understand some general processes and the consequences of some decisions, even if not to fully quantify them.

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1 Introduction

1.1 Carbon dioxide (CO_2) cycles naturally between the atmosphere and the biosphere as a result of photosynthesis, respiration, decomposition and combustion. The amount of carbon in an ecosystem changes as it develops and evolves (Ostle and others, 2009). Carbon is absorbed by water, phytoplankton and vegetation, creating significant stores in the oceans, biomass and soils. Globally, soils contain about three times the amount of carbon in vegetation and twice that in the atmosphere (IPCC, 2000; Smith, 2004).

1.2 Human activities are changing directly and indirectly the rate of CO_2 exchange (IPCC, 2000) and the amount of stocks (Ostle and others, 2009) by reducing the capacity of ecosystems to sequester and store CO_2 and by producing significant greenhouse gas (GHG) emissions due to the burning of fossil fuels and to land clearance and deforestation (Broadmeadow and Matthews, 2003). Agriculture is the second largest source of greenhouse gases in the UK but emissions in this sector have been declining steadily since 1990 (Defra, 2010), mainly as a result of changes in agricultural practices, such as reducing the use of synthetic fertilisers (Choudrie and others, 2008). Land management choices can either maintain or increase the carbon store for long periods of time or result in net emissions. Therefore, land use and management choices can have an important role in determining the amount of carbon released into the atmosphere or stored in the soil (mitigation) and, as a consequence, in global climate regulation (Smith and others, 2007; Thompson, 2008).

1.3 Land use change, such as deforestation and agricultural intensification, is a major source of global emissions (about 1.8 Gt C yr^{-1}) (IPCC, 2000). There is also increasing evidence that degraded peatlands are a significant source of CO_2 emissions (Thompson, 2008; Natural England, 2010; Joint Nature Conservation Committee, 2011b). Carbon storage by marine and coastal habitats has been less studied than terrestrial stores, but recent evidence (Laffoley and Grimsditch, 2009) indicates that they may be of comparable importance to terrestrial stores.

1.4 The UK has signed the United Nations Framework Convention on Climate Change and has to prepare annual National Inventory Submissions (NIS). These submissions must include GHG emissions and sequestration from land use, land use change and forestry (LULUCF). Some LULUCF practices, such as drainage, cultivation, deforestation and habitat destruction, result in GHG emissions. Others, such as afforestation, conversion of croplands into grasslands and the restoration of degraded land, result in sequestration (Ostle and others, 2009; Dawson and Smith, 2007; Natural England, 2010).

1.5 By restoring some habitats such as grasslands or bogs, or promoting active accretion of sediments in intertidal systems, land and marine managers can help mitigate the causes of climate change by directly reducing greenhouse gas emissions, safeguarding carbon stores and in some cases re-starting sequestration (Natural England, 2010). The sustainable management of habitats important for carbon storage therefore contributes to meeting targets for GHG emission reductions, including the carbon budgets set by the UK Climate Change Act. According to the UK's NIS, LULUCF activities resulted in a small net sink in 2006 (Choudrie and others, 2008). Sequestration from forestry and arable land use change to grasslands slightly outweighed emissions from peat drainage, peat extraction and land use change to croplands. In some cases habitat restoration may pose a dilemma between increasing carbon sequestration or increasing biodiversity (for example, removal of trees to restore lowland heathland) and land managers will need all the available information to underpin their decisions.

1.6 The work presented here can also contribute to the delivery of Defra's Climate Change Plan (Defra, 2010), in gathering evidence to protect and benefit from ecosystem services and informing:

1) front line stakeholders (for example, land and marine managers);
2) intermediary bodies (such as farming associations); and
3) other government departments.

Project rationale

1.7 Natural England reviewed and published the evidence on the role that land and marine managers can play as 'carbon managers' (Thompson, 2008). The review identified the key evidence gaps that need to be filled for woodlands, peatlands, agricultural land and coastal/marine systems. It also scoped the potential for land and marine managers to engage with the carbon market (for example, through offsetting schemes), but concluded that until key evidence gaps are filled there is limited potential for new revenues.

1.8 The UK's NIS would benefit from an improved understanding of the carbon storage of the full range of English habitats under different conditions and management regimes. To achieve this goal we should try to increase the number and improve the accuracy of the records of GHG emissions from the management of terrestrial and marine carbon sinks. This will, in turn, ensure that the contribution that land and marine managers can make to climate change mitigation through habitat restoration and sustainable management practices will be recognised in climate change policy.

1.9 This report does not deal with other important green house gases such as nitrous oxide (N_2O) or methane (CH_4), although some information is presented where relevant.

1.10 This project had three main objectives:

1) To produce an overview of carbon storage and GHG fluxes by a range of English terrestrial and marine (inter and sub-tidal) habitats, taking account, as far as possible of the effects of management, habitat condition and factors such as soil and sediment characteristics. This is presented in the form of a readily understood table which was being updated regularly throughout the project, reflecting the fast-developing nature of the field (see Annex 1). This data can be used to inform the improvement of the UK LULUCF inventory. Such an overview is not currently available although NERR026 (Thompson, 2008) provided a starting point.
2) To review and develop understanding of carbon storage and fluxes in coastal and marine habitats in a specific English context. The work of Laffoley and Grimsditch (2009) provides a global overview of coastal habitats, but application to our own situation is an important next step.
3) To carry out targeted research to fill key evidence gaps, particularly for peatlands and coastal and marine habitats. Work on peatlands is reasonably well-developed but it is necessary to follow this through to ensure delivery of field research results which can be applied in practice (for example, research on the effects of restoration on methane emissions needs to continue for a number of years to allow equilibrium to be established). Other areas, for example links between land management in catchments will require scoping before commissioning any new research in subsequent years. We are working closely with other organisations, such as CEFAS, on obtaining relevant information on changes in carbon storage for coastal and marine habitats.

Audience

1.11 This report focuses on objectives 1 and 2 above only, although relevant information from current research on peats and marine habitats is included where relevant. It is mainly aimed at those working on climate change mitigation; to inform the development and delivery of

Environmental Stewardship and related issues in the context of CAP reform; and at Natural England environmental specialists and should be seen as a stepping stone for further research on this matter.

Definitions and technical terms (most taken from the IPCC 2000 report)

CO_2-e: (CO_2-equivalent or equivalent CO_2): The concentration of carbon dioxide that would cause the same amount of radiative forcing as a given mixture of carbon dioxide and other greenhouse gases.

Carbon sequestration: The process of increasing the carbon content of a carbon reservoir other than the atmosphere. Biological approaches to sequestration include direct removal of carbon dioxide from the atmosphere through landuse change, afforestation, reforestation, and practices that enhance soil carbon in agriculture.

Carbon sink: Any process, activity or mechanism that removes a greenhouse gas or a precursor of a greenhouse gas from the atmosphere.

Carbon source: Any process, activity, or mechanism that releases a greenhouse gas or a precursor of a greenhouse gas into the atmosphere.

Carbon stock: The absolute quantity of substance of concern (for example, carbon or a greenhouse gas) held within a reservoir at a specified time. A reservoir is a component of the climate system, other than the atmosphere, which has the capacity to store, accumulate, or release a substance of concern. Oceans, soils, and forests are examples of reservoirs of carbon.

Teragramms of carbon (Tg C): equal to Megatons of carbon

Conversion of carbon units into CO_2 units: multiply by 3.66667

2 Terrestrial habitats

2.1 The Countryside Survey 2007 (CS2007) estimated the carbon stock of soils in England as 795 Mt C. However, this survey only sampled the first 15 cm of soils, therefore not accounting for the amount of carbon stored deeper, particularly in peats. England had the lowest carbon density in GB due to the lower frequency of carbon rich soils in this country. In a supplementary paper, Chamberlain and others (2010) showed that the largest topsoil C stocks (measured down to 15 cm) were contained in the broad habitats with the largest extent: arable and horticultural fields, improved grasslands and bogs. There were however significant differences (by a factor of 300) within broad habitats and some locations were extremely heterogeneous, making it difficult to generalise.

2.2 The CS2007 did not confirm the loss of soil carbon reported by another key study (Bellamy and others, 2005), except for arable and horticultural land. Chamberlain and others (2010) reported that the CS2007 figures are similar to those in other European countries and the discrepancies are probably due to the survey structure and the methodology used by Bellamy and others (2005) which overestimates the carbon bulk density and uses different conversion factors. However, a recent review funded by Defra (project SP1101) rejected this hypothesis and suggested the differences may have been a result of the sample site selection.

2.3 The following sections provide an overview of the main stocks for each broad habitat and the relation between the condition, and the management required to achieve it, and the implications for the carbon cycle.

Grasslands

2.4 This section covers semi-natural and semi-improved grasslands. Improved grasslands (those regularly fertilised and/or ploughed and reseeded) are considered within the agricultural habitats section as their management may be more akin to agricultural land and will have different soil properties. Grasslands are components of other broad habitats and as such they may be included under coastal habitats such as sand dune, or heathlands. Semi-natural grasslands are only 3% of the grasslands in England (Natural England, 2008) but since their soils are less disturbed than those under improved grasslands they are still important in terms of carbon storage. Ninety seven per cent of semi-natural grasslands were lost between 1930 and 1983 and the decline still continues in some areas. Chamberlain and others (2010) indicate that losses in habitat area are likely to be more significant for the carbon stocks than management factors.

2.5 The main broad types of semi-natural grasslands, in relation to the substrate they occur on are: acid, calcareous and neutral grasslands, in both, uplands and lowlands. Lowland grassland (mostly below 350 m altitude) are defined as being enclosed by fences, hedges, walls or ditches, to distinguish them from the unenclosed uplands. This category includes six species-rich Priority Habitats listed in the UK Biodiversity Action Plan: Calaminarian Grassland, Lowland calcareous grassland, Lowland dry acid grassland, Lowland meadows, and Upland hay-meadows (some over 350 m). Although *Molinia-Juncus* grasslands are a type of fen according to some classifications, they are also considered in this section.

2.6 The basic management of grasslands, from the vegetation point of view, is aimed to reduce standing biomass annually. This is usually achieved by grazing, silage or, in the case of hay meadows, cutting for hay and aftermath grazing. These management options are unlikely to have a significant effect on the soil carbon fluxes, unless they result in soil erosion and disturbance. However, carbon stocks can be affected by changes in farming methods and policies, including both intensification and neglect.

2.7 Grasslands have a relatively simple structure compared to many other habitats, with one principal layer of vegetation, the herbaceous sward, and some patches of bare ground and scrub (Joint Nature Conservation Committee, 2004a). The condition of grasslands is determined by looking at a series of primary attributes (habitat extent and specified features of the sward according to grassland type) and secondary attributes (sward height, litter accumulation and bare ground).

Grasslands and carbon

2.8 As in other habitats, most of the carbon store in grasslands is in the soil. Grasslands soils have the highest carbon stock of any UK broad habitat[2] (NEA, 2011). But whereas podsols store an average of 193 t C ha^{-1}, brown calcareous earths store 117 t C ha^{-1} and humic-alluvial gley soils store 438 t C ha^{-1}, to mention just a few types (Milne and Brown, 1997). The CS2007 did not find significant differences in the mean carbon concentrations of grasslands in England over time, although acid grasslands showed significant increases in carbon density from previous surveys.

2.9 Grazing can result in the consumption of a large proportion of the annual above ground net primary production. As grazing by livestock is the most common grassland management, there are also carbon emissions resulting from the animals' biology (ruminants or not) and the way they are managed (intensive or extensive farms). For more information on livestock impacts see section on agricultural land (2.68 – 2.74). Taking all factors into account Ostle and others (2009), citing the IPCC LULUCF reports, concluded that grasslands remaining as such were net emitters of 0.2-0.3 Mt C yr^{-1}, whereas Janssens and others (2005 – cited in NEA grasslands) suggested that UK grasslands (they did not differentiate between improved and unimproved types) sequestered 242±1990 kg C ha^{-1} yr^{-1}. In any case, it has been estimated that a change in land use from grasslands to arable land has resulted in 14.29 Mt CO_2 emitted to the atmosphere from 1990 to 2006 (Choudrie and others, 2008).

2.10 The species composition of grasslands influences the amount of carbon in the soil. Fornara and Tilman (2008) showed that high-diversity US grasslands stored 500% more soil C than monocultures and that legumes and C4 grasses[3] were the main contributors. C4 grasses are not common in England, except for a few species which occur in dunes or saltmarshes, rather than in grasslands (for example, *Spartina anglica*). However, De Deyn and others (2010) showed that seeding *Trifolium pratense* in grassland restoration sites in the UK led to significant increases in soil carbon sequestration (3.17 t C $ha^{-1}yr^{-1}$ in the most successful treatment), more than just by increasing species numbers. Given the results in other parts of the world, it could be expected that other legumes may have a similar impact in grasslands and other habitats.

Grassland condition and carbon

2.11 Appendix 1 shows the percentage of Sites of Special Scientific Interest (SSSIs) for each grassland type in favourable or unfavourable recovering condition in England was (note that some of the condition data may cover coastal cliff top grasslands) as November 2010. Upland calcareous grasslands have the lowest area in favourable condition (19%), but reflecting the great restoration effort in the last few years, they also have the highest in unfavourable recovering condition (78%).

[2] This figure is likely to include (semi)improved grasslands

[3] C4 carbon fixation is one of three biochemical mechanisms (besides C3 and CAM photosynthesis), used by plants in carbon fixation

2.12 Appendix 2a shows the main reasons recorded by Natural England for unfavourable condition which may be relevant for carbon accounting. Appendix 3 indicates how management choices impact on the carbon cycle. In general, lowland meadows, lowland calcareous grassland, lowland dry acid grassland and lowland forms of *Molinia-Juncus* all suffer more from lack of management and/or undergrazing. Upland hay meadows are prone to agricultural intensification (too high levels of fertilisers and overgrazing outside the shut-up period). Upland calcareous grasslands and other grasslands above the level of enclosure generally suffer from overgrazing. The grazing levels impact on the amount of litter accumulation, which in turn results in more or less carbon sequestration, mainly in the organic layer. Britton and others (2005), Conant and Paustian (2002) and Ostle and others (2009), among others, showed that reducing grazing pressure in overgrazed systems resulted in increased carbon sequestration, particularly in wetter systems. Other management options, such as scrub control and cutting/mowing are expected to have the opposite effect. However, Van Den Pol Van Dasselaar and Lantinga (1995) found that the rate of increase in the amount of soil organic carbon was higher under grazing than under mowing. In all cases the highest risks of carbon emissions are more related to soil disturbance than to changes in the vegetation structure. However, soil compaction in grasslands (all grasslands, not just semi-natural ones) has been identified as a limiting factor on soil organic carbon (SOC) (for example, Boghal and others, 2009). Relieving compaction, despite resulting in further soil disturbance, is considered to increase SOC, although Boghal and others (2009) only give percentages rather than estimates of actual SOC increases.

2.13 Drainage affects especially lowland meadows and *Molinia–Juncus* pastures and results in carbon losses as a result of the oxidation of the organic matter (Natural England, 2010; Bellamy and others, 2005).

2.14 Intensification of agricultural practices includes fertiliser application and re-seeding (with or without ploughing), which result in loss of biodiversity of semi-natural grasslands. However, small amounts of fertiliser have been shown to increase carbon sequestration (Van Den Pol Van Dasselaar and Lantinga, 1995) but it is not clear whether this result could be a reflection of past management (for example, previous ploughing) (R Jefferson pers. Comm.). Intensification will also lead to an (un-quantified) increased emissions from fossil fuel use. C reduction from ploughing may also be due to mixing and dilution of C in topsoil rather than a loss.

2.15 Table 1 shows some headline figures (see Annex 1) for grasslands in general. Note: much of the literature does not differentiate among priority habitat types.

Table 1 Carbon consequences of some management options in grasslands

Grassland Condition	**Management option**	**Annual Carbon exchange (+ emissions; -sequestration) ($MtCO_2$-e yr^{-1})***	**Area Carbon exchange (+ emissions; - sequestration) (tCO_2-e ha^{-1} yr^{-1})**
Degraded	Peat extracted	+0.422 (Choudrie and others, 2008)	
Restored (from other land use or improved grassland)	Restoration	-8.72 (Choudrie and others, 2008)	-11.62 (De Deyn and others, 2010)
Maintained	Biomass burning	+0.13 (Choudrie and others, 2008)	
Maintained	Grazed		-2.20 (De Deyn and others, 2010)
Land use change	Grassland to arable	+14.29 (Choudrie and others, 2008)	+3.48 +3.67 to +6.23 (Dawson and Smith, 2007)
Land use change	Grassland to afforestation		-0.37 (Dawson and Smith, 2007)
Land use change	Grassland to wetland		-2.39 to -14.30 (Dawson and Smith, 2007)
Restored	Restore un-improved grasslands (soil + veg, yr 1)		-6.96 (Warner, 2008)
Restored	Restore unimproved grasslands (soil + veg, yr 2-39)		-4.03 (Warner, 2008)

Figures for this and subsequent tables are for the UK

*Annual C exchange figures are from UK GHG Inventory

Knowledge gaps

2.16 There is no detailed information on the impact of grazing regimes on the storage capacity of different grassland and the relation to condition, except Fornara and Tilman's (2008) work on species richness but this work was carried out in the US.

2.17 Also, little is known about the role of grassland re-creation and restoration of semi-improved grasslands in increasing C sequestration rates and about the C sequestration and impact of management practices and species composition. Further research would be welcome on the role of fertiliser in carbon sequestration, to determine whether past management is the influencing factor. One way to test this would be to look at the soil C in grasslands that have been agriculturally-improved by fertiliser addition but have not been ploughed (and reseeded).

2.18 However, there are a series of projects currently under development which may provide more information. For instance, the DEFRA/NE WEB is a five year multi-factorial project, which is measuring the total soil C in grassland swards established using a variety of simple, low-cost methods and subject to different management treatments. The project objective is to investigate which establishment methods/management treatments are best for increasing general biodiversity and enhancing ecosystem services (agronomic value, pollination, pollution reduction, mitigation of climate change) and could be applied easily across substantial areas of the countryside via ELS. Early results showed that the ploughing treatment substantially reduced total soil C at both experimental sites (40% and 10-15%), its magnitude seemingly influenced by different land-use histories.

Dwarf shrub heath

2.19 This section deals with semi-natural habitats characterised by dwarf shrubs of the heath family and gorses. In the UK they are roughly divided into Upland and Lowland heathlands at about 300 m of altitude. Most heathlands are a product of centuries of human use and management. However, there are situations in mountain and coastal habitats where the climatic and soil conditions will maintain heaths in a climax stage, as open vegetation. The differences between upland and lowland heathlands have more to do with historical and current management, as ecologically there is a continuum.

2.20 Most of the carbon stock associated with these habitats is in the soils. Heathland soils are characteristically acidic and nutrient poor. The soil types vary greatly depending on the parent material, including wind deposited sand and loess, glacial and fluvial deposits and peat. In terms of carbon storage, wet heaths, with a more peaty soil are more significant stores than drier heath on sandy or other mineral soils or dune heaths. Milne and Brown (1997) suggested that podsols (common under upland and lowland heaths) contain about 10% of England and Wales soil carbon, equating to approximately 175-211 t C ha^{-1}, which is relatively high for non-peat soils. On the other hand, brown sands, the most likely result of agricultural improvement of sandy heathland soils, contain approximately 93 t C ha^{-1}. Perhaps somehow counter-intuitively, Barton and others (1999) showed that carbon concentrations in some heathland soils were greater than in forest soils in the same area, particularly in the mineral horizons. Carbon emissions are likely to result from disturbance to the soil, both as a result of damage (trampling, loss of vegetation cover) or management and restoration practices, such as top soil removal or soil inversion (Hawley and others, 2008).

2.21 Heathlands in good condition are defined by a diverse vegetation structure and composition, the presence of patches of bare ground, grassy areas and scattered trees (Joint Nature Conservation Committee, 2009). The openness of most of these habitats is a result of continuous management and use over the centuries and achieving favourable condition still requires constant intervention. Without it, in most situations, the habitat will lose the openness and will be invaded by bracken, scrub and trees, or be replaced by tussocky grasses, potentially leading to increased carbon sequestration, but also to the disappearance of the characteristic animal and plant species.

2.22 As at November 2010, 11.5 % of the upland heathlands were in favourable condition, whereas 86.3% were in unfavourable recovering condition. The figures for lowland heathlands are 27.6% and 65.3% respectively. The main reasons, relevant for carbon accounting, for heathland sites being in unfavourable condition are indicated in Appendix 2a. They are mainly undergrazing and excessive scrub cover in the lowlands and overgrazing and excessive burning in the uplands.

Heathlands and carbon

2.23 There have been various estimates of the carbon stock on heathlands. Rough estimates are an average of 88 t C ha^{-1} in the soil (CS2007) and 2 t C ha^{-1} in the vegetation (Ostle and others, 2009) which would add up to 29.8 Mt C in England (using the extent from the CS2007 report (331k ha) for this broad habitat. The rate of carbon sequestration varies depending on the growth stage of the vegetation; whereas the bare ground stage may be a net source, the building and mature stages are net sinks and there is no significant sequestration in later stages (Table 2).

2.24 CS2007 did not find any significant changes in the amount of carbon in this habitat from 1970s to the last survey. However, given the broad definition of this habitat, the above figures may include areas of other habitats such as bog or bracken which may have undergone some changes.

2.25 Warner (2008) estimated the emissions of heathland HLS options (in t CO_2-e $ha^{-1} yr^{-1}$). Whereas creating heathland from arable lands (HO4) would result in a net sequestration of carbon (-5.44), maintenance (HO1) has a negligible effect in carbon fluxes (-0.07); restoration from neglect (HO2) results in a slight emission of carbon (+2.56), and restoration from forestry (HO3) changed the system from net sequestration to slight emission (+4.46 t CO_2-e $ha^{-1} yr^{-1}$). The value was -3.05 t CO_2-e $ha^{-1} yr^{-1}$ for HO5, creation from mineral sites.

Heathland condition and carbon

2.26 The UK BAP targets seek the re-creation of over 11,300 ha of lowland heath by 2020 (UK BAP, 2006), much of which will be on agricultural and forested land. There is also a target to restore (i.e. improve the condition) of a further 10,500 ha of existing heathland. Hawley and others (2008) reviewed the impact of commonly used heathland restoration and/or re-creation techniques on soils (including the carbon stock) and archaeology. The impact of these techniques on carbon storage seems to depend not so much on the objective (for example, removing trees), as on the way it is performed. For instance, whereas there could be a significant loss of carbon from rapid clear felling, carbon stocks could be maintained with a more gradual felling cycle (Broadmeadow and Matthews, 2003).

2.27 Colls (2006) used Tomorrow's Heathland Heritage[4] project data from the mid 1990s for an unpublished MSc project. She calculated that 0.09 Mt C were released as a result of heathland restoration and re-creation activities involving tree and scrub clearance (0.03 and 0.06 Mt C respectively). However, the figures depended on the final fate of the arisings and whether they were burnt or left to decay. Fifty per cent of the vegetation and wood dry weight is carbon (Broadmeadow and Matthews, 2003), which is released when burnt. Legg and Davies (2009) reviewed the impact of different burning regimes on heathlands. They concluded that fire is an integral part of most heathland systems and understanding the role of the vegetation as fuel, the climatic conditions, the ignition, location and timing could help to determine when a fire had a "good" or "bad" impact on the habitat condition. In the short term, burning results in a release of carbon into the atmosphere. However, in the long term, "cool" fires that do not damage the organic content of the soil can be considered carbon neutral or even carbon positive when averaged over a fire cycle (Clay & Worrall 2008 cited in Legg and Davies 2009). On the other hand, hot burns may release carbon from the organic matter in the soil (Forgeard and Frenot, 1996).

2.28 As a broad principle, those heathland restoration techniques which rely on soil removal or disturbance are more likely to cause carbon emissions than those which rely only on vegetation changes (Broadmeadow and Matthews, 2003). However, there is some evidence that they tend to be more effective in restoring the habitat (Hawley and others, 2008).

2.29 Drainage of wet heaths (as in peats), for agricultural intensification or game management, results in the oxidation of the soil organic matter and releases CO_2, mainly as dissolved organic carbon (DOC) (Holden, 2009).

2.30 On the other hand, re-creating heathlands from arable land and/or restoring the hydrology would result in increased carbon sequestration, both in the vegetation (for example, peat

[4] Tomorrow's Heathland Heritage (THH) was the name of the umbrella programme which, over 10 years, aimed to restore and re-create lowland heathlands. The programme was funded with £14 million by HLF and match-funded with over £12 million from more than 150 project partners. It consisted of 23 projects, most of them in England, two in Wales, one in Northern Ireland and one in Scotland

forming mosses) and in soils. This would go some way to redress the potential loss from tree clearances (Milne and Brown, 1997).

2.31 Evans and others (2006a) looked at a further factor which affects negatively the condition of heathlands and the vegetation composition: nitrogen enrichment from atmospheric deposition. Nitrogen deposition increases carbon accumulation and stimulates vegetation growth and greater litter production (Vitousek and others, 1997) and reduces decomposition rates by limiting the carbon available to microbes (Berg and others, 1998; Hagedorn and others, 2003). The research by Berg and others (1998), though, was in a nitrogen-saturated site, which may not be very representative of other heathland sites. Evans and others (2006a) calculated that as much as an extra 392 kg C ha^{-1} yr^{-1} (1.44 t CO_2-e ha^{-1} yr^{-1}) could be absorbed into the soil as a result.

2.32 Other external factors, such as climate change, may also have an impact on the amount of carbon stored or emitted from heathlands, as well as increasing fire risk. Gorissen and others (2004) found that C in soils decreased 60% with experimentally induced drought in just two months. Emmett and others (2004) also found increased accumulated surface litter with experimentally increased temperature (2-22%).

2.33 Table 2 shows some headline figures (see Annex 1) for heathlands in general.

Table 2 Carbon consequences of some management options in heathlands

Habitat & Condition	Management option	Annual Carbon exchange (+ emissions; - sequestration) ($MtCO_2$-e yr^{-1})	Area Carbon exchange (+ emissions; - sequestration) (tCO_2-e ha^{-1} yr^{-1})
Upland heath – degraded	planted with birch	Average +14% in 20yr (Mitchell and others, 2007)	
Lowland heath – Maintained	Burning, grazing, scrub clearance		+0.07 (Warner, 2008 – average 5 yrs)
Lowland heath – Restored	Scrub removed		+2.56 (Warner, 2008 – average 5 yrs)
Lowland heath – Restored	Trees removed		+4.46 (Warner, 2008 – average 5 yrs)
Upland heath – Agriculturally improved	Change to grassland		+3.30 to +4.03 (Dawson and Smith, 2007)
Lowland heath – Restored	from arable (soil yrs 1 to 100)		-3.32 (Warner, 2008)
Lowland heath – Restored	from arable (vegetation yr 1)		+7.45 (Warner, 2008)
Lowland heath – Restored	from arable (vegetation from yr 2-55)		-0.62 (Warner, 2008)
Lowland heath – Restored	from arable (vegetation from yr 56)		0 (Warner, 2008)

Note: the literature in many cases does not differentiate between lowland or upland heathlands

Knowledge gaps

2.34 The available data for this habitat shows huge variations depending on the authors and the geography. As with other open habitats, the management and restoration of heathlands can result in carbon emissions. These habitats are important for the biodiversity and cultural ecosystem services and carbon considerations need to be balanced against these other factors. Better figures of carbon emissions under different management options would help with the decision making.

Woodlands

2.35 Woodlands in this country have been through many changes during history, including cycles of deforestation and reforestation. Currently only 13% of Great Britain (10% of England) is wooded (Forestry Facts and Figures 2011) and only 1.2% is ancient semi-natural woodland, a valuable and irreplaceable natural resource. Over much of the twentieth century there was substantial woodland planting to reach the current area of forest cover, which is a considerable increase compared to approximately 5% in the 1920s; forest creation has however declined dramatically since the late 1980s. This section includes all woodland types.

2.36 Despite their relative low cover in this country, woodlands make a very important contribution to carbon dioxide sequestration in the UK (Thompson, 2008). Their carbon dynamics and potential to contribute to climate change mitigation have been subject of substantial study; this account is simply a summary. More detailed information can be found in Read and others (2009).

2.37 The condition of many semi-natural woods in England is threatened by neglect or inappropriate management. The Forestry Commission have a policy against clearance of broadleaved woodland for conversion to other land use, and towards conservation of the character of ancient semi-natural woodlands (Defra and Forestry Commission, 2005). The table in Appendix 1 shows the broad woodland types in England and their current condition, although being SSSI figures they represent just c. 10% of the woodland. The main reasons and area recorded for woodlands in unfavourable condition, which may influence the carbon cycle, are shown in Appendix 2a. Excessive grazing (deer in the lowlands, livestock in the uplands) and inappropriate forestry and woodland management are the most important impacts identified.

2.38 Semi-natural woodlands in good condition should have appropriate structural complexity and variability, show natural regeneration and locally distinctive vegetation composition (Joint Nature Conservation Committee, 2004c).

Woodlands and carbon

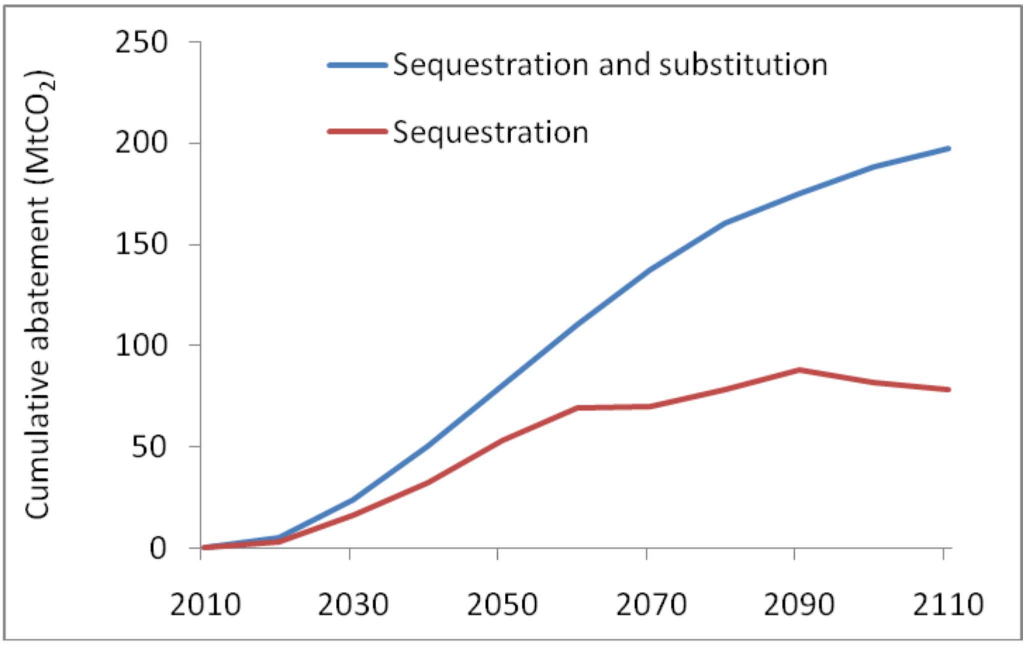
2.39 In a recent review of the role of forests under a changing climate Read and others (2009) estimated that UK forest (including soils) currently store 790 Mt C (or 2897 Mt CO_2-e). Woodlands remove a further c.15 Mt CO_2 yr^{-1} (2007 data, Read and others (2009)). Carbon sequestration rates in trees, woody vegetation and soils vary with species, site condition and management but are broadly similar per unit area to many other habitats. However, the storage of carbon in the vegetation is higher and builds up over decades to centuries because of the formation of wood. Woodland has an additional benefit for climate change mitigation in that wood fuel and forest products can substitute fossil fuels and reduce the need for materials such as concrete, the production of which produces substantial greenhouse gas emissions.

2.40 Rates of sequestration are likely to decrease in the next few years, because of the increase and then decrease planting over the last few decades: many stands are currently at the fast growing ‘stem exclusion’ phase, where carbon sequestration rates are highest and will soon be felled under normal forestry practice. Read and others (2009) estimated a reduction in the C sequestration potential of British woodlands from current values to a projected 4.6 Mt CO_2 by 2020. The extent of this decline will be modified by different management strategies. In the longer term woodland creation offers the potential to significantly increase the overall sequestration of carbon by woodland in the UK. Read et al (2009) concluded that with a woodland creation scheme to increase forest cover to 16% land area, by the 2050s, woodland could be delivering emissions abatement equivalent to 10% green house gas emissions at that time. Of the total carbon storage of 790 Mt C in UK forests, Read and others (2009) estimated that 640 Mt C was in the litter and soils compared to 150 Mt C in trees at the UK level. The figure for trees in England was 63 Mt C. Estimation of soil carbon is complicated by the considerable variations in soil depth but CS2007 estimated the soil carbon stock in the top 15 cm in England to be 63 t C ha^{-1} for broadleaved woodland and 70 t C ha^{-1} for coniferous woodland. This gives a total of 80 to 85 Mt C, depending on the source for the extent figures: 1,238,000 ha according to CS2007 or 1,297,000 ha according to Forest and Forestry Facts 2011.

2.41 A separate study, the EU project BioSoil, is monitoring soil biochemistry and biodiversity. There are 167 sites in the UK (72 in England). Measurements include full soil chemistry down to 80 cm depth (incl. C and bulk density). Results indicate that UK forests (trees) contain about 550 Mt CO_2 (i.e. equivalent to UK's emissions in a single year). UK forest soils contain about 4 Gt CO_2. This is nearly 1.5 times more than the estimates by Read and others (2009); the disparity may be explained by the different depth of the samples.

2.42 Soil carbon is essential to take into account in evaluating decisions about woodland creation. Afforestation of open habitats and croplands may increase the carbon in the soil, but the same is not true of plantations on peaty soils. As a result of afforestation, peat-based soil may dry out, releasing large amounts of carbon. The carbon balance in the early years of a plantation is negative, as more carbon is lost during the peat drainage than that sequestered by a stand up to 12 yrs (Cannell and Milne, 1995). A similar effect has also been seen in 20 yr-old birch trees planted on heathland, with control heather plots having higher percentage of carbon than in the birch plots (Mitchell and others, 2007). The carbon emissions in young planted woods may be offset by sequestration by other vegetation colonising the open area (Broadmeadow and Matthews, 2003).

2.43 After establishment, carbon sequestration increases substantially as growth rates increase before slowing down when the trees reach maturity, and then the rate falls, but old growth stands continue to show net sequestration with a build up of litter and dead wood (Figure 1). In managed woodlands, the substitution value also typically increases as larger timber is produced. The soil processes slow down and continue sequestering carbon for longer periods, although greatly influenced by the management choices.



‘Substitution’ in this context means carbon emission reduction when fossil fuel and other materials are replaced by woodland products. Redrawn from Read and others (2009)

Figure 1 Cumulative potential emissions abatements from mixed objective forestry

2.44 This pattern is not constant across sites as the National Soils Resources Institute (NSRI) study showed that in around half of conifer and broadleaf woodland soils soil C increased, whereas in the other half soil C decreased. Broadmeadow and Matthews (2003) estimated that, on average, commercially managed stands accumulate up to 100 t C ha^{-1}.

2.45 The choice of management options and species has a significant impact on the potential of a woodland to store carbon (Broadmeadow and Matthews, 2003), although carbon storage needs to be balanced against other objectives for woodland management, including conservation. Different strategies have different benefits. At one extreme, minimal intervention can allow carbon stocks to build up and there are fewer emissions from forestry operations. On the other hand, if the objective is to store carbon rapidly, then choosing fast growing species on fertile land could be the best option. In the medium term conifers are a better choice than hardwoods, but in the long term (100+ years) oak and beech store as much as conifers (Dewar and Cannell, 1992). Table 3 gives an indication of the impact of various forest management alternatives (adapted from Read and others 2009).

Table 3 Indicative estimates of whole tree carbon stocks (t CO_2eq ha^{-1}) and annual mid-rotation rates of carbon sequestration (t CO_2eq ha^{-1} $year^{-1}$) that may apply to each forest management alternative

	Unmanaged forest nature reserve	Close-to-nature forestry	Combined objective forestry	Intensive even-aged forestry	Wood biomass production
Carbon stocks	800	500	(450)	400	(200)
Annual rates	6	(11)	(16)	22	29

Values in parentheses are extrapolated from other measures, see ‘Notes’ in original report for further detail on extrapolations and assumptions

2.46 In practice, minimum intervention is more likely to be chosen for slow growth stands and areas in which there is no demand of wood products or for conservation objectives. Commercial woodland management can result in carbon emissions through fossil fuel use, thinnings and soil disturbance, but it may also lead to C abatement through use of the wood products. In this case, the combined product and vegetation over 300 yrs is likely to be greater for fast growing conifers than broadleaves. As much as 19 Mt C (69 Mt CO_2-e) (Read and others, 2009) are found outside forests, in wood products such as paper, joinery and timber (Broadmeadow and Matthews, 2003). The substitution of fossil fuel by wood-based products in effect means very long term storage. Read and others (2009) estimated that the replacement of fuel by sustainably-produced wood could save 7 Mt CO_2 yr^{-1}.

2.47 A number of factors affect the potential of woodlands to sequester carbon. Grazing impacts on woodlands flora (Kirby, 2001) but also on the carbon stock by removing biomass in the understory (Tanentzap and Coomes 2011). The large amount of litter in forest soils contributes to their carbon sequestration capacity. This has been shown in studies of agricultural land colonised by secondary woodland (Poulton et al., 2003).

2.48 Some researchers (Peterson and Melillo, 1985; Schindler and Bayley, 1993; Townsend and others, 1996; Holland and others,1997) consider that air pollution as a result of nitrogen deposition may have a positive effect on the carbon storage capacity of woodlands (as reported too for heathlands), both in biomass and soils. Evans and others (2006b) showed that where atmospheric nitrogen deposition leads to carbon accumulation, nitrogen enrichment of the soil (expressed in terms of C/N ratio) will be slowed, or potentially halted.

Knowledge gaps

2.49 Carbon cycling in woodlands has been relatively well studied in comparison with other habitats but much of the published information comes from models (as for other habitats). Further studies to validate these models and determine the geographical and woodland type variation are required. In particular soil carbon dynamics are much less well studied than sequestration from tree growth.

2.50 There are good opportunities to integrate biodiversity conservation and a wider range of ecosystem service provision with carbon management and timber production. How to optimise the different range of benefits in different situations is an important issue. It is also important to develop the evidence base to allow landscape and catchment scale approaches and identify where woodland planting will have optimal benefits.

2.51 Heath and others (2005) showed that increased atmospheric CO_2 availability results in short term growth and C accumulation in forests; but in the long term it leads to increased microbial respiration and emissions. Therefore, in the future woods may not be as efficient carbon sinks as expected. Thus, current and future estimates may need to be adjusted accordingly. On the other hand increasing CO_2 makes leaves more water-use efficient so may allow greater C uptake.

2.52 There is great potential for developing new markets for woodfuel, timber and wood products in a low carbon economy. How harvested wood is used (for example, to replace other materials in construction) may have as much of impact on overall emissions as the conditions under which it was grown.

Wetlands

2.53 Wetlands are defined as “areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water the depth of which at low tide does not exceed six metres” by the Ramsar Convention on Wetlands of International Importance (1971). Therefore, wetlands cover a broad range of habitats and landscapes, and care must be taken when comparing carbon storage across them. In this report *Molinia-Juncus* grasslands are considered in the grassland section (section 2.4 – 2.18) and saltmarshes are considered with other coastal habitats (section 3.9 – 3.12).

2.54 The condition of wetlands is determined by a series of factors, including the supply, movement and chemical attributes of water, the level of hydrological complexity and topography (Joint Nature Conservation Committee, 2004b). Structure is more important in determining the quality of some wetlands (for example, raised bog) than for others (for example, fringes of a river).

2.55 Appendix 1 shows the percentage of SSSIs for each wetland type in favourable or unfavourable recovering condition in England as at November 2010. The attributes and features that determine favourable condition in wetlands are, as the component habitats, very variable, but hydrology is a significant factor. The main reasons recorded for unfavourable condition, in relation to the carbon budget are indicated in Appendix 2a. Although each wetland type is subject to different pressures, overgrazing and burning in the upland bogs, and siltation and drainage issues are issues to highlight.

Wetlands and carbon

2.56 Carbon sequestration is most significant in wetlands where vegetation is characterised by hydrophytes, and conditions are saturated for much of the year, preventing decomposition of plant matter and driving the formation of peat. Globally, wetlands are considered a vital terrestrial carbon sink (Kayranli and others, 2010), with peatlands storing 0.1 - 0.46 t C $ha^{-1} yr^{-1}$, prairie wetlands around 3.05 t C $ha^{-1} yr^{-1}$, agricultural field and rivers 1.6 - 2.2 t C $ha^{-1} yr^{-1}$ and some constructed wetlands accumulating up to 22 t C $ha^{-1} yr^{-1}$. It can be assumed UK wetlands play a similar role in the UK's carbon balance. Ostle and others (2009) estimated that peatlands store over 550 Mt C in GB, whereas a report by Natural England (2010) provides a breakdown by type: blanket bog and valley mire storing 138 Mt C; raised bog 57.5 Mt C; lowland fen in which deep peat deposits have been maintained 144 Mt C and 'wasted' lowland fen, which have been substantially degraded by agricultural conversion 186.4 Mt C.

2.57 UK peatlands have been accumulating carbon since the ice age, as the amount of carbon sequestered is greater than that lost via decomposition processes, with net accumulation rates estimated at 0.2 - 0.5 t C $ha^{-1} yr^{-1}$ (Clymo and others, 1998; Cannell and others, 1999). However, this value is likely to have a large uncertainty attached due to the relatively interchangeable use of the terms 'wetlands' and 'peatlands' in the literature.

2.58 Throughout England wetland habitats were once extensive. However drainage, agricultural expansion, peat extraction and urban development on flood plains have reduced their extent. According to the Wetland Vision Partnership, 44% of lowland raised bogs have been drained, between 20 - 40% of reedbeds lost, and 75% ponds have declined in the last 150 years (Hume, 2008). The loss of the waterlogged, anaerobic conditions of these habitats means that the rate of carbon sequestration has declined, and in some cases like the Fens, has even been reversed.

2.59 Carbon storage in England's wetlands has received relatively little attention until recently, and as such few biogeochemical studies have been undertaken on many of these very varied habitats. Peatlands, including blanket bogs, raised bogs and fen peats, are the exception due to their extensive land cover and agricultural and economic potential. England's peatlands cover 11% of its area and are estimated to contain 584 Mt C (Natural England, 2010). The CS2007 looked at broad habitats types and within these included the following wetland habitats: fen, marsh and swamp (0.95% England's land area) and bog (1.1%). The study sampled the top 15 cm of soil, estimating soil carbon stock of each: for example, fen, marsh and swamp (76 t C ha^{-1}), bog (74 t C ha^{-1} or 259 ± 8 t C ha^{-1} when extrapolated to 50cm depth), but made no estimate to the carbon stock of the vegetation. Ostle and others (2009) suggested that approximately 2 t C ha^{-1} is contained within heath and bog vegetation, equating to 14% of the UKs vegetation carbon stock.

2.60 Wetlands also act as transitions between terrestrial and aquatic systems making it difficult to pinpoint the fate of carbon lost from these systems. In their attempt to quantify the role inland aquatic systems play in the global carbon budget Cole and others (2007) suggested that the amount of carbon that is transported to the atmosphere is twice that of the carbon delivered to the oceans via lake, river and estuarine pathways. As the carbon dioxide released to the atmosphere is mainly from the aquatic decomposition of organic matter, this suggests that inland aquatic systems oxidise a substantial proportion of the organic matter they receive from the land.

2.61 Land use change from wetlands to other habitat tends to result in a net carbon loss – drainage and disturbance of wetlands leads to hydrological shifts causing changes to carbon cycling, decomposition and fluxes (Billett and others, 2004). While damaged wetlands can be restored and carbon sequestration increased, it does not compensate for the net C accumulation in the original system before disturbance (Waddington and Price, 2000) meaning wetland protection is preferable to restoration.

2.62 Studies of UK stream and lake catchments have reported increases in dissolved organic carbon of up to 100% (Freeman and others, 2001; Worrall and others, 2003) suggesting significant losses from terrestrial systems. Such increases may indicate decreasing storage of carbon or an increased rate of carbon cycling (Worrall and others, 2004) highlighting the need further research into the carbon balance of England's varied wetlands habitats.

Table 4 Carbon consequences of some management options in wetlands

Habitat	Management option	Annual Carbon exchange (+ emissions; - sequestration) ($MtCO_2$-e yr^{-1})	Area Carbon exchange (+ emissions; - sequestration) (tCO_2-e ha^{-1} yr^{-1})
Blanket bog & Valley mire	Cultivated & temporary grass		+22.42
Blanket bog & Valley mire	Improved grassland		+8.68
Blanket bog & Valley mire	Peat extracted		+4.87
Blanket bog & Valley mire	Rotationally burn		+2.56
Blanket bog & Valley mire	Restored	-0.86	
Raised bog	Semi-natural		-4.11
Lowland fen (deep)	Semi-natural		+4.2
Lowland fen (deep)	Cultivated & temporary grass		+26.17
Lowland fen (deep)	Improved grassland		+20.58
Lowland fen (deep)	Peat extracted		+1.57
Lowland fen (deep)	Afforested		+2.49
Lowland fen (deep)	Restored	-1.14	
Lowland fen (wasted)	Cultivated & temporary grass		+4.85

All data adapted from Natural England (2010)

Knowledge gaps

2.63 Further differentiation is needed between England's distinct wetland types and their individual contribution to the UK's carbon balance. Wetland research tends to focus on the boreal systems due to their vast areal cover and soil carbon stocks. However, positive management of England's wetlands could result in significant gains in carbon sequestration. Dawson and Smith (2007) cite gains of 0.1 – 1 t C ha^{-1} yr^{-1} when wetlands undergo restoration. Revegetation of wetlands from arable and grasslands could result in greater carbon gains of 2.2 – 4.6 t C ha^{-1} yr^{-1} and 0.8 – 3.9 t C ha^{-1} yr^{-1} respectively. However, these estimates have a high level of uncertainty attached.

2.64 We cannot yet predict accurately net changes in greenhouse gases (CO_2, CH_4 and N_2O) fluxes as a result of peatland restoration through rewetting. They are likely to be site-specific and depend on the previous land uses, including whether the soil N has been enhanced (Maljanen and others, 2010). Uncertainties around emissions of methane, a particularly potent greenhouse gas, are a major factor.

2.65 The status of many wetlands as greenhouse gas sinks means they act as an important buffer to rising atmospheric carbon dioxide levels. More research is required to understand how England's wetlands will respond to climate change. The majority of carbon in wetland habitats is typically stored below ground in their soils. This is significant as carbon stored deep below the surface turns over more slowly and is better protected from disturbance. However, the effect of climate change on these vast carbon stores is unknown, with suggestions that they could switch from sink to source. There is a strong correlation between climate and soil carbon stores as temperature is a key driver of decomposition rates. Warmer climates would result in increased release of carbon in the form of carbon dioxide and methane, with rates dependent on the changes to the hydrological processes and water tables that would also occur (Kayranli and others, 2010).

Arable and horticultural land

2.66 Agricultural land currently covers 71% of England's terrestrial area and, for this report, includes cropland, intensively managed grazing land, farm woodland and set aside. The active management of this land, coupled with its large area, means it plays a significant role in England's carbon balance. Intensification, drainage of lands and the decline in mixed farming systems all act to alter the cycling of carbon in the farmed environment.

2.67 Only a small proportion of agricultural land is designated as SSSI under as "Arable and Horticulture", "Boundary and Linear Features" and "Improved Grassland". The area in favourable and unfavourable recovering as November 2010 is in Appendix 1. The main reasons for agricultural SSSIs being in unfavourable condition, in relation to carbon budgets, are indicated in Appendix 2a. In general, the presence or absence and/or cover of a series of indicator species, both positive and negative, determines the condition of farmland habitats.

Farmland and carbon

2.68 The main carbon losses from agricultural systems result from increased rates of decomposition of soil organic matter and losses via erosion of the topsoil, which contains a greater percentage of organic carbon (Dawson and Smith, 2007). Bradley and others (2005) estimated that arable land stores around 583 Mt C and that there were 686 Mt C within the first 100 cm of soil under pasture (permanent managed grassland, as opposed to grassland which receives no management). According to their calculations, this stock was larger than that of other semi-natural habitats, woodland, arable land or gardens. Bellamy and others (2005) reported soil carbon losses of 0.6% yr^{-1} (relative to soil carbon content in 2005) across England and Wales between 1978 – 2003, and changes in agricultural management over a similar period may have played a role in the decline (Dawson and Smith, 2007). However, other studies (CS2007) dispute the scale of these losses (see the introduction to section 2 (2.1 – 2.3)).

2.69 Whether agricultural soils are a carbon sink or source depends on a number of wide ranging variables including climate, soil type, land use, water availability and, most importantly, the actual organic matter content of the soil (Freibauer and others, 2004). Agricultural practices based around grasslands are predicted to be a net carbon sink while arable land is a net source. Freibauer and others (2004) cite mean carbon flux measurements of 0.60 t C ha^{-1} y^{-1} and -0.83 t C ha^{-1} y^{-1} respectively in a review of European soils. Studies of UK soils concur with this, however at lower rates. Ostle and others (2009) estimated that all UK grasslands (including semi-natural) sequester 240 ± 200 kg C ha^{-1} y^{-1}, while croplands lose 140± 100 kg C ha^{-1} y^{-1}. Despite covering such a large proportion of the UK the arable and grassland vegetation carbon stock accounts for only 6% of the UK's total, equating to approximately one tonne per hectare (Ostle and others, 2009). However, the vegetation carbon stock is of immense importance in agricultural systems as it represents the main carbon input to the soil (Leake and others, 2006). Land use changes in the agricultural sector would be expected to result in a shift in the carbon balance. Between 1990 and 2000 the conversion of grassland to arable cropland has been identified as the largest single contributor of soil carbon loss from land use change in the UK (Ostle and others, 2009; Thomson and van Oijen, 2007) with potential losses up to 1.7 t C ha^{-1} y^{-1} (Dawson and Smith, 2007; Ostle and others, 2009). However, Warner (2008) indicated that the loss is not constant. Rather, it has been found to be at an exponential rate and the C sequestered will be lost and returned to its original equilibrium more rapidly than it was gained.

2.70 Conversion of arable land to grassland has been suggested as the most effective option for carbon mitigation by a number studies (Vleeshouwers and Verhagen, 2002; Smith and others, 2001), especially when that land would be considered surplus or abandoned.

2.71 Livestock numbers have declined, and their management intensified, resulting in less animal manure being spread on fields which once acted to return carbon to agricultural soils (Burton and Turner, 2003; Dawson and Smith, 2007). Grazing or the lack of it can also influence soil chemistry and biota, which in turn impact on the carbon cycle (Bardgett and others, 1997; Neilson, 2002). Warner (2008) provides methane and N_2O estimates of emissions from livestock, but not carbon equivalent. However, he also calculated the impact of growing food for farm animals (use of fertiliser, ploughing, etc) and the production of silage.

2.72 Improvements in plant breeding and farm machinery has lead to an increase in the amount of biomass harvested each year meaning a reduced amount of crop residue is left on the field. Production of silage, at the expense of hay, has increased. This again leads to greater removal of plant residues and further decreases soil carbon stocks (Poulton, 1996, cited in Dawson and Smith, 2007; Shepherd and others in preparation). Tillage of arable land has been strongly linked to erosion, and the associated loss of organic matter and soil carbon: for example, no till farming sequesters 0.39 t C ha-^{1} yr-^{1} vs. 0.08 t C ha^{-1} yr^{-1} with till and medium N-fertiliser application (van Oost and others, 2005; Dawson and Smith, 2007).

2.73 Some agricultural habitats can have both a significant biodiversity and carbon storage importance despite their small extent. This is the case of orchards. The most comprehensive study of this habitat (Robertson, Marshall, Slingsby & Newman, 2012), which looked at a selection of traditionally and industrially managed orchards, found that most carbon was stored in the soil, rather than the trees, and that this soil store was smaller than that of woodlands and permanent grasslands. The carbon in orchard trees is also less than in woodlands, as they are usually maintain in a "dwarf" size. The land use history influenced the amount of soil carbon, particularly cultivation. A significant amount of carbon in the orchards is in the fruit, which is removed (and transformed) annually. The main GHG emission resulted from the use of tractors and enteric fermentation by grazing livestock. However, part of these emissions is offset by the accumulation in the trees.

2.74 As shown below, intensively managed orchards sequester more C per year, although traditional orchards have a greater C density, both in the soils and the vegetation. This can probably be explained by the fact that soils in the traditionally managed sites is less disturbed and the production (biomass) in the intensively managed is greater.

Table 5 Carbon consequences of some management options for agricultural land in general and improved grasslands

Habitat	Management option	Area Carbon exchange (+ emissions; - sequestration) (tCO_2-e ha^{-1} yr^{-1})
Orchards	Traditional	-0.10 (Robertson and others, 2012)
Orchards	Intensive	-4.66 (Robertson and others, 2012)
Arable land	Change to grass (50yrs)	-1.10 to -2.93 (Dawson & Smith, 2007)
Arable land	Change to forestry (115 yrs)	-7.52 (soil+veg) (Dawson & Smith, 2007)
Arable land	Change to wetland	-8.07 to -16.87 (Dawson & Smith, 2007)
Arable land	Ploughed (20 cm)	0.09 (Warner, 2008)
Arable land	Subsoil tramlines	0.02 (Warner, 2008)
Arable land	Pesticide application	0.01 (Warner, 2008)
Improved grassland	Change to woodland (soil + veg, yr 1)	-7.83 (Warner, 2008)
Improved grassland	Change to woodland (soil + veg, yr 2-21)	-13.7 (Warner, 2008)
Improved grassland	Change to pollen & nectar mix	-5.87 (Warner, 2008)

Knowledge gaps

2.75 Much of the evidence above comes from carbon cycling models based on a limited number of studies, within which assumptions and generalisations have been made. Further research is required to determine the accuracy of these models over extended periods of time as uncertainties at the European scale can be very large, often in the region of being greater than 50% (Freibauer and others, 2004). Future climate change will alter agricultural carbon stocks as changes in precipitation patterns and temperature will affect conditions for plant production, decomposition and animal husbandry as a result. A site status as a carbon sink or source is dependent on many variables, one of which being soil type. Studies (Ostle and others, 2009) suggest that of the soil types present in the UK, organic or carbon rich soils are most sensitive to climate change. Therefore, further insight is needed into how reductions of soil moisture and increased temperatures could release these carbon stocks. High levels of uncertainty are attached to many predictions of the effects of agricultural land use change, again for the reasons described above, and due to farming practices differing from farm to farm (Bell and Worrall, 2009).

2.76 Due to its large size, England's agricultural land has significant potential to increase its carbon storage. Land use reversion, erosion control, low or zero tillage, organic matter additions, rewetting drained land and crop management are just several examples within the literature of improving agricultural carbon storage. What currently is not clear is how these suggested methods will affect the carbon storage in the long term; how this would be further affected by future environmental change; how any gains would affect or link to other nutrient and hydrological cycles; and the impact of farm productivity. Furthermore, when advising on carbon sequestration in agricultural practices, care must be taken to avoid "carbon leakage", when reversion of arable land results in compensatory conversion of carbon rich land elsewhere, possibly abroad, such as grassland, peatland or woodland, to arable usage (Ostle and others, 2009). In the case of the UK the leakage is likely to be displaced production going overseas.

2.77 Orchards have received little attention until recently and most data is extrapolation from other habitat studies. However, a recent inventory and a report (Robertson and others, 2012) will provide much needed information. More precise studies of the impact of grazing and mechanical management would be necessary, as well as finding uses to non-fruit products, such as wood from pruning.

Terrestrial habitats summary

2.78 Most carbon in terrestrial habitats and wetlands in England are in the soils. Therefore, adopting management options which reduce the soil disturbance, erosion and oxidation is likely to result in increased carbon stores.

2.79 The condition of designated sites can be improved by adopting options, which in many cases will benefit both the site biodiversity and the carbon store in the vegetation and the soils.

2.80 The main knowledge gaps across habitats are: the impact of changing grazing regimes; the carbon consequences of management choices; testing models in the field at small scale; the impact of habitat restoration on other GHG emissions; the impact of climate change on carbon cycling; and the impact of all the above on farm productivity.

3 Coastal and marine habitats

3.1 The National Ecosystem Assessment (2011) indicated that carbon sequestration rates are high in saltmarsh, sand dunes and machair as a result of rapid soil development or sediment accumulation; but total area of these habitats is low. Sand dunes on the west coast of the UK store 0.58 to 0.73 t C ha^{-1} yr^{-1}, while saltmarsh is estimated to store 0.64 to 2.19 t C/ha/yr (Cannell and others, 1999). The conservative estimate of carbon stocks in coastal margin habitats is at least 6.8 Mt C.

3.2 However, production in the marine environment is dominated by phytoplankton, and therefore there is relatively low C sequestration and storage in this pool. In contrast, coastal vegetated ecosystems accumulate 50-70% of the carbon permanently stored in the marine ecosystems globally (Duarte and others, 2005) despite covering <0.5% of the seabed (UNEP, 2009). This is due to flowering plants, seaweed and kelp detritus carbon being resistant to decomposition (Enríquez and others, 1993) and therefore more likely to store carbon in the medium – long term.

3.3 This role in coastal and marine habitats is now being recognised and Table 6 summarises storage capacity of these habitats along with an approximate total storage of C for England where estimation was possible. It is worth noting that these values are poorly constrained and should be considered as a guide only with fluxes of C into and out of these habitats often poorly understood.

Table 6 Area and associated C storage for the range of marine and coastal habitats in England

Habitat	Area (ha) in England	C sequestration g C m^{-2} yr^{-1}
Sea grass meadow	?	20-200 Romero and others (1994)
Kelp forest	?	~400 Gevaert and others (2008)
Saltmarsh	33,572 EA 2006-2009 Aerial photo interpretation	210 Chmura and others (2003)
Intertidal mud	33,608 Mudflat Inventory (MasterMap, 2002)	16 Andrews and others (2006)
Sand dunes	12,880 English Nature GB sand dune survey (1990s)	58-73 Jones and others (2008)
Subtidal coarse and sandy sediments (to 12 nautical miles)	3,139,363 Assuming 61% of inshore seabed composed of coarse and sandy sediments (Joint Nature Conservation Committee, 2011a)	>10 Painting and others (2010)

3.4 The area and percentage of SSSIs for each coastal/marine type in favourable or unfavourable recovering condition in England, as at November 2010, is indicated in Appendix 1. Some of the main reasons recorded for unfavourable condition, in relation to carbon budgets, are in Appendix 2b, with coastal squeeze, inappropriate coastal management and water pollution and/or agricultural run-off among those more significant. Given the variety of habitats included in this section, the number of attributes to determine favourable condition is also highly variable, including extent, range of biotopes, density of vegetation, topography, sediment character, etc.

3.5 The main coastal and marine habitats involved in coastal and marine C sequestration are outlined below.

Sand dunes

3.6 Although the contribution of arid and semi-arid areas globally has been investigated in terms of carbon sequestration (Lal, 2004), there seems to have been limited consideration of the role of temperate sand dunes. However, as table 6 shows, this habitat is potentially responsible for a significant amount of carbon storage as a result of soil organic matter accumulated due to the production of litter and dead roots (Berendse and others, 1998). Many factors are involved in influencing sand dune C storage, for example, vegetation type, which is important in soil development; or the impacts of productivity and litter biochemistry (Berendse and others, 1998; Gerlach and others, 1994). Higher levels of organic matter are associated with dunes under shrubs or trees (Jones and others, 2008 and references therein). Sand dunes also increase their capacity for C storage with age, with sand dune organic matter still increasing after 50 years or more (Olff and others, 1993; Jones and others, 2008).

3.7 Beaumont and others (in prep) estimated the carbon stock in sand dunes in England as 0.40 Mt C.

Knowledge gaps

3.8 The contribution of sand dunes to C storage seems to have been under investigated to date, although the review by Beaumount and others (in prep) will contribute to increase our knowledge. An understanding and estimation of the importance of the various zones in sand dune succession is important if their potential for C storage and management is to be accurately assessed in the future.

Tidal saltmarshes and estuaries

3.9 Salt marsh and intertidal mud form a continuum with the flow of sediment between the two, which is crucial in maintaining these habitats. England possesses extensive areas of coastal saltmarsh and estuarine mudflats. Saltmarsh has two main characteristics which allow them to act as efficient carbon sinks. They have high primary production rate with European saltmarsh soils storing an average of 2.1 t C ha-^{1} yr-^{1} (range 0.77-6.5 t C ha-^{1} yr-^{1}; Chmura and others, 2003 and references therein). A recent estimate for saltmarsh C stock in England by Beaumont and others (in prep) is 2.43 Mt C. Secondly they do not emit methane, an important green house gas, since the sulphide present in the soil inhibits bacterial-driven methane production (Giani and others, 1996; Van der Nat and Middelburg, 2000). The water levels and occurrence of anaerobic decomposers in tidal marsh ecosystems also acts to reduce organic matter decomposition and promote carbon storage (Hussein and others, 2004). Saltmarsh creation from agricultural land therefore results in an increase carbon storage (Connor and others, 2001) in these regions with Andrews and others (2006) estimating that each km^2 of realigned coastal land on the English East coast could result in the burial of additional c. 30 tonnes of C per year.

3.10 Carbon accumulation in saltmarshes is related to both the supply of sediment and the rate of sea-level rise (Morris and others, 1990, 2002). Carbon accumulation increases with sea-level rise until this reaches a critical rate that drowns the marsh vegetation (Mudd and others, 2009) or the coastal squeeze prevents the saltmarsh from retreating in land (Wolters and others, 2005). Managing sediment and nutrient supply to estuaries could therefore lead to significant changes in the carbon budgets of coastal saltmarshes. The impact of nutrient enrichment from rivers and marine sources should also be considered in management since long term nutrient enrichment of saltmarshes reduces below ground carbon storage and may result in reduced marsh elevation. Sustaining and restoring coastal emergent marshes is therefore more likely if they receive reduced nutrient loading (Turner and others, 2009).

3.11 Like saltmarshes, estuaries are highly productive environments and are also areas of accumulation of both marine and terrestrially derived organic carbon (Burdige, 2006) acting as a sink for carbon (Jickells and others, 2000). Their effectiveness for C sequestration is due to the predominantly anoxic nature of both their intertidal and subtidal sediments (Burdige, 2006), thus reducing the decomposition of organic matter leading to a higher preservation of organic carbon within the sediments (Hartnett and others, 1998). For example, the sequestration of C in the Humber estuary is estimated to be 0.16 t C ha^{-1} yr^{-1}, including intertidal and subtidal mud (Andrews and others, 2006). Estuaries that are accreting are therefore increasing their C storage. Conversely the drainage of coastal wetlands results in releases of previously sequestered carbon. The drainage of the Wash is predicted to have released 1400 Mt CO_2 in total (World Bank, 2010). Methane emission from mudflats is not significant due to the presence of sulphides (Stumm and Morgan, 1981).

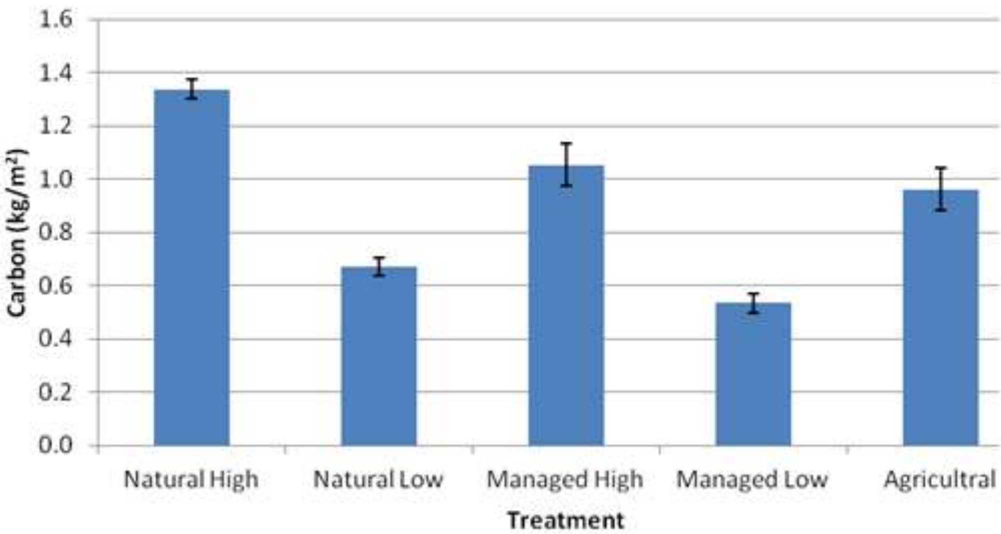


Figure 2 Carbon storage in natural and restored saltmarsh and agricultural soils

3.12 Figure 2 shows carbon storage in the Tollesbury managed realignment (Garbutt in prep), comparing the regenerated saltmarsh (Managed) with the adjacent natural marsh (Natural) at two elevational zones (High/Low). Information was also collated from an adjacent agricultural soil from a field of wheat.

Knowledge gaps

3.13 Although the chemical cycling in estuaries is well understood (Jickells and Weston, 2011), our knowledge of the role of the habitats and in particular the effects of realignment of our coasts on C storage is at an early stage. Research is therefore needed on short term factors such as above and below ground storage of C and effects of nutrient enrichment. More difficult to estimate, but necessary for future predictions are the effects of climate change and sea level rise. In general estuaries and their associated saltmarshes are potentially large C stores. If the driving processes in the carbon cycle can be better understood and linked to favourable condition, then appropriate management may be able to increase the C sink potential of these habitats. However, in most cases, it is the area of the saltmarsh and estuary that is key and not their management.

Sea grass meadows

3.14 Sea grasses can grow in extensive meadows in shallow water, and long-lived sea grasses and are widely distributed in English waters. Sea grass has the potential to sequester large amounts of organic carbon, with one study showing that the sea grasses sequestering 0.2- 2 t C ha^{-1} yr^{-1} in sediments (Romero and others, 1994) although a figure for the sea grasses in English waters (eel grass *Zostera* spp.) could not be found.

3.15 Eel grass beds have suffered a decline in England due to many factors from wasting disease (Short and others, 1998) to the human disturbance from coastal development and water pollution (Parker and others, 2004; Tomasko and others, 2006). It is however challenging to restore sea grass meadows (Orth and others, 2006) with key factors being the controls on sediment loading and water column nutrients. The restoration of eel grass beds frequently fails due to inappropriate site selection: sites often cannot support sea grass or only at low levels (Parker and others, 2004). It is therefore recommended that sites for re-establishment are close to existing areas of eelgrass beds. The colonisation of intertidal mudflats by *Spartina anglica* has also reduced the area available for future eel grass recolonisation (Parker and others, 2004). The management of eelgrass beds and saltmarshes must therefore be considered together.

3.16 In terms of climate change, sea-level rise may cause long-term change to eel grass beds, for example by an increase in the frequency and intensity of severe storms (Parker and others, 2004). Ocean acidification may aid sea grass meadows with macroalgae potentially replaced in some localities by sea grasses as dissolved carbon concentrations increase. Sea grasses, which evolved under higher CO_2 concentrations, are carbon-limited with respect to photosynthesis under current concentrations (Harley and others, 2006).

Knowledge gaps

3.17 The main challenge with sea grass is the difficulty in restoring sea grass beds with progress being slow both in the UK and globally. Water Framework Directive (WFD) monitoring and implementation will improve our knowledge of the distribution of the sea grass meadows.

Macroalgal beds

3.18 Macroalgal beds, i.e. composed of seaweeds, are found on shallow hard substrata in temperate coastal waters and are widespread around Europe (Steneck and others, 2002). Kelp forests are a type of macroalgal bed composed of large brown seaweeds (kelp) characterised by long strap-like blades reaching up to 10 m length, restricted to rocky sea beds to a depth of typically <30 m due to light limitation (Scheil and Forster, 1986; Fuller, 1999). Suitable substrates for macroalgae growth include rock, boulders, cobbles and human-made structures from the intertidal zone. *Laminaria* spp. and *Fucus* spp. are the main genera along the coasts of northwest Europe. Modelling using UKSeaMap 2010 (marine summary of evidence) indicated that 24% of the UK inshore seabed is rocky habitat (Joint Nature Conservation Committee, 2011a) so there is considerable distribution of suitable substrate for kelp and macroalgae.

3.19 Unlike other coastal habitats, since kelp forests are found on rocky substrates, there is no burial of organic matter. However, there is a large associated standing stock of C, ranging globally from 1.2 to 7.2 t C ha^{-1} (Reed and Brzenzski (2009) and references therein). An example of kelp relevant to English coasts is *Laminaria digitata* which has a standing stock of c. 4 t C ha^{-1} (Gevaert and others, 2008). Kelp forests also affect the physical properties of the water column by reducing waves and water flow. In turn, this will influence coastal sedimentation and erosion and benthic primary production (Duggins and others, 1990) with benthic algae representing approximately 20% of the standing crop (Reed and Brzenzski (2010) and references therein).

3.20 Management of kelp forests may be difficult since kelp beds can be rapidly lost due to storms, water column warming or grazing events but their high productivity allows for quick recovery (Scheibling, 1984; Harrold & Reed, 1985; Hart & Scheibling, 1988; Witman, 1988; Tegner and others, 1997). The canopy of kelp at the seabed reduces light, creating suitable understory conditions for low light adapted algae (Santelices and Ojeda, 1984). Climate change may have significant effects on kelp distribution since they are sensitive to increased water column temperatures (Davison, 1991; Izquierdo and others, 2002) and excessive light exposure (Hanelt and others, 1997).

3.21 Macroalgal blooms of seaweeds, such as *Ulva* spp., are a potential problem in UK waters (Jones and Pinn, 2006). In estuaries with increased nutrient input macroalgae blooms can result in ecosystem level changes (Lavery and McComb, 1991). These blooms may also be long lasting. For instance, in Massachusetts, blooms of *Cladophora* and *Gracilaria* have been present over 20 years (Valiela and others, 1997).

3.22 Land use practices that affect coastal nutrient regimes will therefore impact kelp and macroalgae to different degrees but operations that result in increasing turbidity will be detrimental to both.

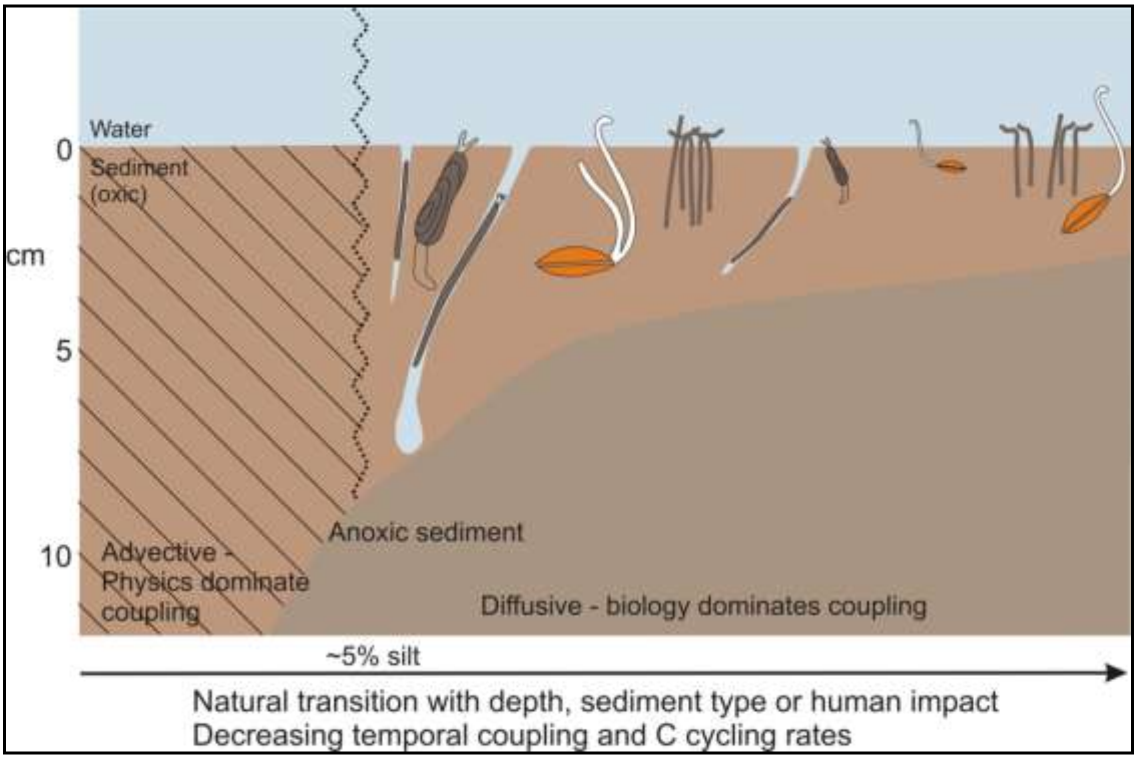
Knowledge gaps

3.23 More work is needed to understand the potential for these habitats as C sinks in English waters and the practices that may help support them. Marine Protected Area, WFD and Marine Strategy Framework Directive (MSFD) monitoring and implementation will improve our understanding of the distribution of kelp and macroalgae habitats.

Subtidal sediments

3.24 The storage and cycling of carbon in shelf sea sediments is largely driven by the physical characteristics of the sediment and the associated infauna (Figure 2). English coastal waters are dominated by coarse sandy sediments which allow water to flow freely through the upper parts of sediment. This results in oxygen penetration allowing rapid C cycling and therefore low carbon storage in these sediments.

3.25 As the sediments become finer and muddier, physical processes, such as water flow, become less important and slower processes controlled by diffusion take over. As for estuarine mudflats, the anoxic portion of these fine sediments reduces the decomposition of organic matter leading to a higher preservation of organic carbon. Although these muddy sediments are less widely distributed, they are generally associated with estuaries and are close to the coast, for example, northern of Liverpool Bay, Lyme Bay and areas close to the Tyne, and are often associated with Dublin Bay prawn *Nephrops* spp. fishing grounds. As shown in figure 2, macrofauna (such as *Nephrops*) have an important role controlling C cycling in muddy sediments since its role in bioturbation helps oxygen penetration in the sediments.



(Reproduced with permission of R Parker, Cefas)

Figure 3 Sediment types and associated infauna and C cycling rates

3.26 For muddy sediments, any activity that affects the mixing of the sediments, including disturbing the infauna, will affect C storage. For example, commercial fishing using bottom trawling will shift the infauna towards short lived small species and can change amount of C in food web and how much carbon goes into detritus (Duplisea, 2001). Storm events that resuspend these sediments will also result in a loss of stored carbon (Duplisea, 2001) as it is remineralised in the water column. In deeper summer layered ('stratified') waters, C input into the water column may not result in increased C exchange with the atmosphere since this water may be transported to the deep ocean. This water transport to deeper waters effectively sequesters the respired carbon over long time scales (Thomas and others, 2004) and is called the shelf sea carbon pump.

3.27 Mixing events, such as trawling or storms, will not however affect carbon storage in coarse sediments since biomass is processed rapidly and not stored in these sediments. For these sediments it is the introduction of fine particles to sediment that is important, such as by aggregate dredging. In this case the open structure of the coarse sediments will change to a muddy substrate resulting in an increase in carbon storage. Any attempt to increase the carbon storage capacity in coarse and muddy sediments function must take into account the sediment type as the key parameter.

Knowledge gaps

3.28 Marine processes are now better understood but quantifying the C cycle, and linking sedimentary processes to water column processes, and these in turn to management options and habitat restoration, is in its early stages. Despite the prominent role of the coastal oceans in absorbing atmospheric CO_2 and transferring it into the deep oceans via the continental shelf pump, the underlying mechanisms to this process remain only partly understood.

3.29 Climate change may also have profound effects on sediment biogeochemistry potentially moving marine habitats from net C uptake to net C production.

Marine habitats summary

3.30 The recognition of coastal and marine habitats as carbon stores is at a much earlier stage than for terrestrial habitats, but recent reports on ‘Blue Carbon’ (UNEP, 2009) seem likely to change this. The implantation of European and national legislation (WFD, MSFD and Marine and Coastal Access Act) will also improve the monitoring programmes and help to understand C storage.

3.31 Coastal habitats are better understood and quantified than offshore habitats. A key question to be answered is perhaps ‘How much C do we want stored in these habitats?’ with some areas such as offshore sediments storing little C per unit area but important in driving the coastal food web and ultimately fisheries. Although offshore sediments store considerable amounts of C overall there is little likelihood that they can be managed to increase C storage whereas increasing saltmarsh area will have a proportionately larger effect. Coastal habitats such as saltmarshes and estuaries also provide important C sources to our coastal seas. It is therefore only by looking at how all these habitats link that we will understand marine C storage and how their management affects C budgets in our coastal ecosystems.

4 Conclusions

4.1 The previous sections showed that, despite various uncertainties, there is enough evidence to provide advice on appropriate land, coastal and marine management options. There is an ongoing need for research in this area, but we can make a series of general recommendations which can already have a wide application and could increase carbon stocks. Among them:

- reducing disturbance and erosion of terrestrial soils and coastal and marine substrates and sediments;
- maintaining and restoring biodiverse native habitats is preferable to (re)creating them;
- even in intensively managed agricultural land, there should be scope for introducing native habitats and species that contribute to carbon sequestration in the most marginal areas;
- reducing the waste from both, the agricultural and forestry production cycles, and from restoration activities by finding alternative use for biomass which is currently burnt or disposed of in landfields;
- selecting appropriate species, such as perennial and deep rooted crops, or legumes can contribute to carbon sequestration in some circumstances;
- using light to moderate grazing levels, both in semi-natural habitats and in intensive holdings; and
- blocking drains and restoring water tables in peatlands.

4.2 A fuller list of recommendations can be found in Dawson and Smith (2007).

4.3 Chamberlain and others (2010) estimated the room for improving the carbon stocks of different habitats and concluded that the four broad habitats with the capacity to hold an extra 100 TgC were those with the greatest extent, i.e. bogs, neutral (improved) grasslands, arable and horticultural and improved grasslands. If the land was managed to retain carbon, the last two showed the greatest potential, sequestering the equivalent to 1.7 and 5.3 years worth of UK annual emissions respectively.

4.4 There are, however, a number of uncertainties and gaps in our understanding of GHG fluxes to and from different habitats in different conditions. It is likely that the UK's NIS is under-estimating GHG emissions from the management of a number of key carbon habitats, such as from the drainage of upland blanket bog. There are also uncertainties on the GHG implications of restoring some habitats, for example the significance of methane emissions following re-wetting of drained peatlands. The role of coastal habitats, such as saltmarsh, is largely unknown. It is also acknowledged that the condition of a habitat and the associated physical soil and sediment processes will have an impact on its potential capability to sequester or emit GHG. Therefore, meeting biodiversity targets could result, in some cases, in a larger carbon store in soils or biomass (Smith and others, 2007).

4.5 There are implications for C storage and cycling (CO_2 draw-down but also on production) for marine management decisions, such as the creation of MPAs and SACs, in terms of moving human activities into other locations. Baseline carbon cycle and storage processes, and the potential effects of ecosystem scale impacts such as marine fisheries on the natural carbon balance need much more investigation. The timescales of storage are very variable, from transient to permanent (i.e. months to years to decades to centuries). There are also geographical variations in the carbon cycle, i.e. different rates of sequestration and emissions. It would be helpful, for example, to understand the importance of living vs. detrital and organic/inorganic matter (including carbonate systems, key for pH).

4.6 Further evidence on the impact of management options and habitat condition is needed to help achieve the target of 80% reduction in GHG emissions by 2050 and 34% reduction on CO_2 by 2020 (UK Climate Bill, 2008).

Table 7 Carbon stock average estimates by broad habitat

Habitats	**Carbon stock in soils (t Cha^{-1})**	**Carbon stock in vegetation (t Cha^{-1})**
Dwarf shrub Heath	88	2
Acid grassland	87	1
Fen, mash and swamp	76	?
Bog	74	2
Coniferous woodland	70	70
Broad leaf, mixed & yew woodland	63	70
Neutral grassland	60	1
Improved grasslands	59	1
Arable and horticulture	43	1
Coastal margins (UK)	48	?

There is no similar data for marine habitats in England or the UK

Data on terrestrial habitats soils from CS2007 in England [Note – CS2007 figures are from 15 cm depth soil samples]; on coastal and marine habitats from NEA 2011 UK-level; on vegetation from Ostle et al 2009, except for woodlands which comes from Broadmeadow and Matthews 2003 and it is an average for 50 yrs rotations

5 Implications for future work

Environmental Stewardship

5.1 The review presented in this report could inform future development and delivery of Environmental Stewardship by trying to prioritise management options which have been demonstrated to maintain soil and vegetation carbon stocks or reduce their losses. This review has shown that those options which do not involve disturbing the soil are the best in terms of conserving those stocks, particularly organic soils. When disturbing the soil is unavoidable, the less deep the disturbance reaches the better. The impact of habitat restoration is not clear-cut, in terms of the carbon implications. Restoring habitats on organic soils may increase carbon sequestration, but it may also increase the release of other GHG. When restoring semi-improved grasslands by introducing a seed mix or green hay the standard advice is to create up to 50% bare ground by heavy harrowing. Clearly, this may be initially negative from a C perspective but longer term such restored grasslands would be expected to build up C levels.

5.2 The situation with the vegetation is more complex. All vegetation, in terrestrial, coastal and marine habitats stores carbon. Mostly the amounts of carbon are relatively small, although in woodland they can be very substantial. However, other objectives (such as maintaining biodiversity, preserving a landscape or even economical factors) are likely to be the predominant influence on management decisions and can result in carbon losses. This would be the case when restoring open habitats from forestry.

5.3 The review has not looked in depth into the role of different types of livestock in the carbon cycle of farmed systems. As a result of their physiology they may release GHG, but they may contribute to the conservation of soil carbon by maintaining a diverse habitat.

5.4 There are other projects currently looking at how to integrate ecosystem services into ES, as many options clearly have the potential to enhance the delivery of certain services. An on-going project is Defra's "The provision of ecosystem services in the Environmental Stewardship scheme" (CTE1004).

Approach to designations and landscape scale conservation

5.5 Looking to the future, a new approach to designated site protection is on the agenda, following the publication of a new White Paper and England Biodiversity Strategy in 2011. Increasingly conservation is being approached at a landscape scale and taking an Ecosystem Approach. Carbon storage is likely to be increasingly considered alongside a wider set of ecosystem services. Accurate quantification is a necessary starting point for rigorous assessment of the relative merits of different sites and approaches to management.

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Appendix 1

Table A Area of each priority habitat for SSSIs in England in favourable and unfavourable recovering condition (ha) and percentage regarding the total

Broad Habitat Type	Favourable		Unfavourable Recovering	
	Area (ha)	**Area (%)**	**Area (ha)**	**Area (%)**
Acid Grassland – Lowland	3,088.64	39.21	4,286.76	54.42
Acid Grassland – Upland	9,797.82	35.50	16,856.53	61.08
Calcareous Grassland – Lowland	12,648.18	29.57	28,528.77	66.69
Calcareous Grassland – Upland	1,650.24	19.04	6,750.01	77.86
Neutral Grassland – Lowland	23,900.40	49.57	19,408.49	40.25
Neutral Grassland – Upland	1,562.70	58.59	611.37	22.92
Dwarf shrub heath – Lowland	14,303.49	27.60	33,841.23	65.3
Dwarf shrub heath – Upland	20,827.27	11.50	156,295.10	86.3
Broadleaved, Mixed And Yew Woodland – Lowland	32,962.96	42.06	41,615.21	53.10
Broadleaved, Mixed And Yew Woodland – Upland	6,153.40	40.14	7,944.62	51.83
Coniferous Woodland	22,829.06	93.84	1,440.29	5.92
Bogs – Lowland	624.07	6.98	6,628.01	74.10
Bogs – Upland	19,871.17	11.39	148,193.37	84.97
Fen, Marsh And Swamp – Lowland	8,882.77	33.31	15,125.18	56.72
Fen, Marsh And Swamp – Upland	986.49	46.88	991.03	47.09
Rivers And Streams	1,495.43	18.27	2,667.55	32.60
Standing Open Water And Canals	11,878.99	50.79	7,270.03	31.08
Arable And Horticulture	13,718.36	97.45	267.09	1.90
Boundary And Linear Features	177.46	95.48	2.27	1.22
Improved Grassland	1,193.38	92.25	89.07	6.89
Inshore Sublittoral Sediment	1,171.47	72.30	192.09	11.86
Littoral Sediment	213,870.45	78.55	55,393.47	20.34
Supralittoral Rock	5,066.48	76.41	1,371.29	20.68
Supralittoral Sediment	5,271.29	36.42	7,422.87	51.29

Figures as at November 2010

Appendix 2a

Table B Reasons for unfavourable condition by habitat (terrestrial) and area affected (ha) for SSSIs in England

Habitats		Undergrazing	Overgrazing	Drainage / ditch control	Agriculture	Inappropriate scrub control	Inappropriate cutting/mowing	Inappropriate water levels	Moor burning/ arson fires	Forestry and woodland management	Deer grazing/browsing	Inappropriate weed control	Peat extraction	Water abstraction	Siltation
Acid grasslands	Lowland	277	53	86	3	31	8								
	Upland	10	710	66	137	13									
Calcareous grasslands	Lowland	767	48		15	662	488								
	Upland	72	184		1	32									
Neutral grasslands		1327	342	165	228	735	348	2582							
Dwarf shrub heath	Lowland	1808	62	679		1661	346		554						
	Upland	816	2487	348		207	46		2050						
Broadleaved, Mixed & Yew Woodland	Lowland	402	108			243	123	82		2718	1165				
	Upland	29	635			55	6			333	326				
Coniferous Woodland		48				49				10					

Table continued...

Habitats		Undergrazing	Overgrazing	Drainage / ditch control	Agriculture	Inappropriate scrub control	Inappropriate cutting/mowing	Inappropriate water levels	Moor burning/ arson fires	Forestry and woodland management	Deer grazing/browsing	Inappropriate weed control	Peat extraction	Water abstraction	Siltation
Bogs	Lowland	70.7	14.3	597		773		272		76		35	23		
	Upland	64	4400	1488					1155	103		11			
Fen, Marsh And Swamp	Lowland	597	277	571		615		304		125		77		407	
	Upland	56	12	9											
Rivers And Streams		10	771	88		78		309		4		104		518	1627
Standing Open Water And Canals				351		313		334		215		62		182	328
Arable And Horticulture		40.79				63.73				12.24					
Boundary/Linear Features										0.33					
Improved Grassland		3.8		7.31											

Figures as at November 2010

Appendix 2b

Table C Reasons for unfavourable condition by habitat (coastal/marine) and area affected (ha) for SSSIs in England

Habitats	Coastal squeeze	Water pollution - agriculture/run off	Undergrazing	Water pollution - discharge	Sea fisheries	Inappropriate coastal management	Overgrazing
Inshore Sublittoral Sediment	70.19	95.73		95.73			
Littoral sediment	5354.89	364.51	282.36	277.97	256.48	161.77	130.43
Supralittoral Rock			101.52			12.43	
Supralittoral Sediment	171.78		255.03			345.26	100.35

Figures as at November 2010

Appendix 3

Table D Potential impact of the reasons for unfavourable condition on carbon stocks

Terrestrial habitats	
Undergrazing	Undergrazing results in the accumulation of litter and vegetation. Litter accumulation in turn results in carbon sequestration.
Overgrazing Deer grazing/browsing	Conversely, excessive grazing pressure is detrimental to plant productivity and may lead to a decline in soil organic matter. (Britton and others, 2005; Conant and Paustian, 2002; Ostle and others, 2009). Heavily grazed grasslands store 1.6 t C ha^{-1} vs. 2.4 t C ha-[1] in less intensively grazed (Warner, 2008).
Drainage / Inappropriate ditch control	Drainage results in carbon losses as a result of the oxidation of the organic matter. (Natural England, 2010; Bellamy and others, 2005).
Agriculture	This is a broad category, but it is likely to include some type of ploughing, which releases carbon, and probably application of fertiliser and other chemicals.
Inappropriate scrub control / Inappropriate cutting/mowing	As for undergrazing, this category indicates biomass accumulation in the habitat and therefore carbon sequestration.
Inappropriate water levels	In the context of grasslands, this means that flood meadows, rush pastures and other wet grasslands which are not regularly flooded. Flooding potentially results in CO_2 sequestration (Natural England, 2010) and CH_4 emissions. McNamara and others (2008).
Moor burning/arson fires	Inappropriate burning regimes cause damage to the vegetation cover and the soil's organic layer, resulting in carbon emissions (Garnett and others, 2000).
Forestry and woodland management	In forests and woodlands, this usually means that the woodland lacks structural diversity. As trees in different growth stages sequester carbon at different rates, there may be an unquantifiable impact on the system carbon stock. In open habitats, this usually means that plantations were established in inappropriate sites and/or they are self-seeding into neighbouring habitats. The growth of trees results in carbon sequestration, but the disturbance of organic soils results in significant releases.
Inappropriate weed control	This is particularly important in wetlands, where usually non-native invasive species displace or eliminate native species. They usually have a more vigorous growth, which can result in increased carbon sequestration; but also, by reducing the amount of light that gets under the water surface, they may affect biomass production and nutrient cycling.

Table continued...

Terrestrial habitats	
Peat extraction	There is much evidence that disturbing organic soils, as well as removing peat, results in large releases of carbon into the atmosphere and as DOC into water bodies (for example, Freeman and others, 2001; Natural England 2010; Waddington, 2000).
Siltation	Siltation occurs when water channels and reservoirs become clotted with silt and mud, usually a side effect of deforestation and soil erosion. Erosion results in losses of CO_2, which may end in water bodies. Siltation influences bacterial cycles in the water, which can also have an impact on carbon cycling.
Coastal and marine habitats	
Coastal squeeze	Results in sub-optimal coastal habitats, which are significant carbon reservoirs (Mudd, 2009).
Water pollution - agriculture/run off/discharge	This usually means increased nutrients which in turn result in increased biomass and potentially increase carbon sequestration. However, as there may be species substitution to the benefit of those adapted to higher nutrient loads, the carbon cycling can be negatively impacted (Turner and others, 2009).
Undergrazing / Overgrazing	Same as for terrestrial habitats.
Sea fisheries	Some commercial fisheries techniques (for example, dredging) may have a negative impact on both the sediments/substrate and on the wildlife, which can affect carbon cycling and sequestration rates.
Inappropriate coastal management	Management of the coastline should focus upon the development of a dynamic environment resilient to the action of coastal processes and sea level rise. There is a need to conserve, manage and sustain sediment supplies that feed coastal systems and the landscapes and habitats they support (Natural England Position Statement on Coastal Change).

Natural England works for people, places and nature to conserve and enhance biodiversity, landscapes and wildlife in rural, urban, coastal and marine areas.

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