Actions to minimise loss of current soil carbon and enhance soil carbon sinks in Wales

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1. Introduction

Welsh soils hold a large reserve of organic carbon, however, this store is vulnerable to loss through land use change and anthropogenic perturbation (e.g. climate change). If soil carbon is lost it causes the release of greenhouse gases (e.g. CO_2, CH_4, N_2O) and has negative effects on other ecosystem services such as food security, biodiversity, and water storage. Similarly, there is potential to store more carbon in the soils of Wales. It is therefore vital that we preserve the nation's terrestrial carbon store. Similarly, there is potential to increase carbon storage in soil through changes in agricultural management and the use of waste materials.

In this report we use the best available evidence to estimate the potential effect that changes in land use and agricultural management can play in reducing greenhouse gas (GHG) emissions and enhancing carbon storage in Welsh soils. GHG emissions from animals are not directly considered here. We considered a wide range of mitigation measures the lifespan of which ranged from 1-50 years and considered evidence for the three major GHGs; carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4). Most evidence from the literature was for changes in CO_2 or the surrogate, soil carbon storage. Fewer studies were available for N_2O and very few studies for CH_4. Literature values were collated for all intervention measures and the midpoint of the range reported applied to landcover/soil type combinations present in Wales, except where Welsh studies indicated different values should be used. We evaluated the potential for different land use change strategies to mitigate against GHG over a 50 year timescale (i.e. 2009-2050) and with different levels of farmer adoption. It is assumed all activities are undertaken in Year 1 and the outcomes for soil carbon and GHG emissions are reported over the subsequent 50 year period.

It is important to recognise that although increasing soil carbon can have substantial benefits to the structure and productivity of soils, there is poor evidence about the linkage between many land management activities and changes in soil carbon and net GHG emissions – taking account of CO_2, CH_4 and N_2O. Photosynthetic processes which fix CO_2 in the soil and biomass on a permanent basis are key to reducing the concentrations of the gases in the atmosphere and protection of soil carbon stocks already accumulated should remain a priority.

It is clear that the potential to reduce GHG emissions in soils and biomass has some limitations. There is a limit to soil carbon storage which is possible after any land use or management change because a new equilibrium is reached, so called 'saturation'. Our work indicated the temporal dynamics of the combined activities reached a maximal in the first 30 years but reaches close to saturation after 50 years. To put this into perspective, we calculated the sum of these GHG reduction measures and plotted them against the 2005 baseline agricultural emission figures. Clearly, if these intervention measures are adopted they have the potential to make a difference. If we are looking for a 3% reduction in emissions each year relative to the 2005 baseline then we would be expecting a 30% reduction in 10 years. This is clearly possible. After this point other mitigation measures would need to be revised if the targets are to be met. There also has to be safeguards in place to ensure the permanence of the reduction measures and that benefits in one location are not negated by enhanced emissions elsewhere – so called 'displacement'. We also emphasise that the potential trade-offs and co-benefits of land management options for GHG emissions reductions and other requirements from the land need to be objectively quantified together with full life cycle assessment to ensure the desired outcome on GHG across sectors would be achieved.

2. Greenhouse gas flows and carbon stocks

For Wales in 2007, land use change to forestry and grassland sequestered 2084 kt carbon dioxide equivalent (CO_2 e), and conversion of land to cropland and settlements led to emissions of 1875 kt CO_2 e. In total, land use change led to a net sink of 199 kt CO_2 e. On present trends, the position by 2020 is that the emission rate will be greater than the sink rate because current Welsh forests are becoming mature with reducing rates of growth and carbon uptake. The major components of these sinks and sources are shown in Table 1.

Table 1. Emissions and removals of GHG by Land Use, Land Use Change and Forestry (LULUCF) in 2007, year average and the general trend (Thomson, 2008). Values are in CO_2 equivalents (CO_2 e).

	Emissions (kt CO_2 e)	**Trend over last 10 years**
GHG sinks		
Land converted to forest	1430	Stable conversion rates since year 2000
Land converted to grassland	643	Steady increase
Cropland remaining cropland	11	
Total carbon sink	**2084**	Relatively stable
GHG sources		
Land converted to cropland	1053	Stable
Land converted to settlements	688	Stable
Liming cropland and grassland	44	Slow decline
Harvested wood products	68	Long term increase
Biomass burning	32	
Total carbon source	**1885**	Long term increase

These quantities are based on changes in biomass and soil carbon levels, and associated fluxes of GHGs. Agricultural land use changes are a significant driver of these changes. Mitigation opportunities exist in four main areas:

1. Minimising emissions by conserving soil carbon stocks in organic soils e.g. wetlands.
2. Enhancing net GHG sequestration in organic and mineral soils by improved grassland, and woodland and wetland management.
3. Enhance carbon in plant/tree biomass.
4. Minimise N_2O losses from all soils through better management of nitrogen fertiliser use.

An important factor determining sinks and sources is the high soil organic content of Welsh soils, mainly associated with permanent grassland and the uplands. The most accurate estimate of the carbon stock of Welsh soils is obtained by aggregating comparable data derived from Bradley et al. (2005) and Smith et al. (2007). While Smith et al. (2007) provides a more complete estimate of total stock, the data of

Bradley et al. (2005) are currently used to calculate emissions estimates in Greenhouse Gas Inventories for Wales.

Based on the work of Smith et al. (2007) and Bradley et al. (2005), the Welsh soil carbon stock is estimated to be 409 Mt carbon (1500 CO_2 e). However, it must be recognised that estimates of soil carbon reserves are heavily reliant on the quality of soil maps (degree of ground truthing, map scale, classification type) and on algorithms describing carbon density in soil (Frogbrook et al., 2009). Consequently, estimates of national soil carbon storage from different mapping approaches gives a range of 340-530 Mt carbon (mean 436 ± 27 estimated from 7 different datasets/national soil maps equivalent to 1600 ± 100 Mt CO_2 e; Ibn Malik, 2006).

Approximately half of the total soil carbon stock is located within an area of 492721 ha or 23.4% of the land surface of Wales, predominantly in upland areas and / or areas of permanent grassland. The remaining 76.6% of Wales is covered primarily by mineral soils with low carbon content (Figure 1).

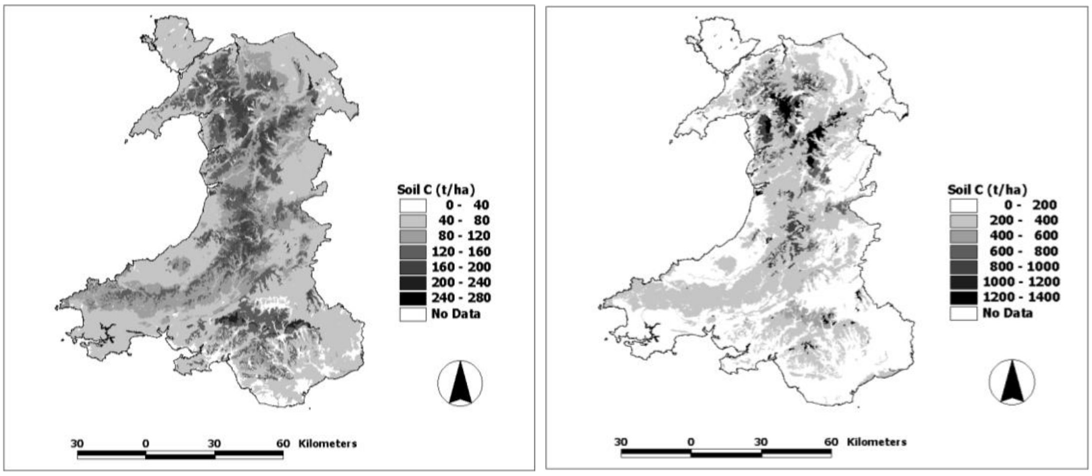

Figure 1. *Distribution of soil carbon in Wales*
The left hand panel represents the amount of carbon stored from a depth of 0-15 cm and the right hand panel from a depth of 0-100 cm (Ibn Malik, 2006).

This report reviews mitigation options in terms of three main soil types, namely; mineral soils, organo-mineral soils, and organic (peat) soils. Soil type is paramount when considering impacts of agricultural operations and land use change, as different soils react differently to the same operation. So a certain operation undertaken on organic soils may reduce emissions while the same operation on mineral soils results in increased emissions. The land cover types were defined using the CEH Land Cover Map 2000 and mapped onto soil types using the NATMAP vector soils data. A summary of the classes and soil type distribution within each land use type is provided in Table 2.

In this report, it was decided to use the Countryside Survey (Carey et al., 2008) as the basis of scenarios for land use change, because the GHG inventory is currently based on the map, and it is updated at regular intervals during the Countryside

Surveys. Methods of improving the LULUCF inventory are being assessed, with particular concern to improve input statistics to track land use change with time – for example, using agriculture statistics data, National Forest Inventory data and Natural Resources Wales Phases1 and 2 data.

Table 2. Soil type versus land use relationships in Wales

Area of land cover types by soil type for Wales

Landcover classes required for LUCCG	Land cover type	Area (km^2) of land cover types by soil type: Mineral	Organo-mineral	Peat
	Cropland			
Cropland	arable cereals	173	3	0
Cropland	arable horticulture	800	27	1
	Total	973	30	2
	Grassland			
Improved grassland	improved	7284	324	22
Semi-natural grassland	setaside	18	0	0
Semi-natural grassland	neutral	667	601	42
Semi-natural grassland	calcareous	1363	74	6
Semi-natural grassland	acid	1585	1268	312
	Total	10918	2267	382
	Wetland			
Fen, marsh and swamp	fen, marsh & swamp	5	7	4
Bog	bog	4	31	21
Saltmarsh	saltmarsh	41	0	0
Ignore	standing/inland water	18	8	1
	Total	68	47	27
	Forest			
Broadleaved forest	broadleaved	1492	87	5
Coniferous forest	coniferous	772	542	106
	Total	2264	630	111
	Urban			
Urban	suburban (built up areas, gardens)	604	63	4
Urban	continuous urban	152	11	1
	Total	756	74	4

Grand total of areas represented	14979	3047	526

Total area of Wales approx 20761 km^2

Notes:
(i) Based on CEH Land Cover Map 2000 25 m data and NATMAP vector soils data (i.e. essentially land use cover versus soil type based on 1998 data)
(ii) No LCM class 43 (arable non-rotational) mapped in Wales
(iii) No classification for man-made soils into mineral, organic, peat
(iv) Results based only on areas where data for both land cover & soils are available

3. Key emission and carbon loss processes

Carbon is largely lost from soil as carbon dioxide (CO_2) as a result of the natural breakdown of soil organic matter by soil microorganisms (Paul and Clark, 1996). The rate of soil carbon loss is maximal in warm, relatively moist and aerobic conditions. This process is also exacerbated by physical disturbance which breaks up soil aggregates, enhancing oxygenation and allows microbial access to physically protected carbon (e.g. ploughing). Methane (CH_4) is produced when organic materials decompose in oxygen-deprived anaerobic conditions, such as permanently waterlogged soils. Nitrous oxide (N_2O) is also generated when soil microorganisms run out of oxygen (e.g. in very wet or compacted soils) and occurs when there is lots of available nitrate (where available nitrogen exceeds plant requirements). It is also exacerbated after addition of nitrogen rich organic wastes to wet soils. N_2O is a much more potent greenhouse gas than CO_2 and CH_4, Therefore, even though loss rates can be small, the resulting climate change effect can be very large.

The exchanges of carbon between the land and atmosphere is dominated by the emission and plant fixation of inorganic carbon (ca. 43.3 Mt CO_2 e/y as Net Primary Productivity (NPP)). Emissions from vegetation include both CO_2 through respiration but also non-methane volatile organic carbon (NMVOC) back to the atmosphere which is a precursor of ozone which contribute 3-7% of the greenhouse effect. Although there is uncertainty in the figures, particularly for grazed grasslands, current estimates for NMVOC loss rates to the atmosphere range from 0.18 to 1.8 Mt CO_2 e/y which equates to a loss of 0.1-1.0% of the total carbon held in vegetation each year representing ca. 0.5-4% of the net carbon fixed by plants in photosynthesis (Guenther, 2002). As forests release more NMVOC's than grassland, it is likely that total NMVOC emissions from Wales are at the lower end of the emission range. The climate change impact of NMVOCs is discussed in Stewart et al. (2003) and Laothawornkitkul et al. (2009).

In reviewing actions to reduce emissions, estimates of soil carbon loss have been based on assuming that all loss is as carbon dioxide and methane emitted to the atmosphere. However, carbon can also be lost from soil as dissolved organic carbon (DOC), particulate organic carbon (POC) and dissolved inorganic carbon (DIC) either from surface erosion, runoff or leaching (Worrall et al., 2007). Monitoring of water quality in Wales has shown that there has been a significant increase in dissolved and particulate organic carbon over the past 20 years, attributed to several factors including reduction of acid deposition and climate change (Evans et al., 2005). Estimates for Wales suggest that the annual loss of carbon to freshwaters is 1.5 Mt CO_2 e with a level of uncertainty ranging from 0.84 to 2.90 Mt CO_2 e. Of this loss, approximately 40% is as CO_2 (due to CO_2 degassing and in-stream breakdown of POC and DOC).

Increasing the soil carbon content can only occur either by increasing carbon input, decreasing carbon output or by a combination of the two through improved land management. Agricultural management systems and forestry operations can strongly influence soil processes such as carbon sequestration and erosion. Examples include drainage of and cultivation of waterlogged organic soils, leading to aeration, increased microbial decay and an associated increase in CO_2 emissions, but decreases in N_2O emissions. Intensive arable use of mineral soils can enhance

N_2O emissions due to the increased rate of de-nitrification associated with excess fertilizer applications, yet it is known that nitrogen is an important driver for fixing more carbon in soils. This emphasises the need to look at all GHG fluxes, and not focus solely on soil carbon. A major gap in our information is an accurate account for all GHG fluxes to and from Welsh soils.

For this sector it is important to recognise that there are significant feedback mechanisms, whereby climate change can exacerbate emissions from soils. It has been reported that topsoils in England and Wales have lost significant quantities of soil carbon over the last 25 years, possibly due to the effects of climate change (Bellamy et al., 2005). This landmark study by Bellamy et al. (2005), however, has been intensively criticized (Smith et al., 2007; Potts et al., 2009; Stutter et al., 2009; Reynolds et al., 2013) highlighting the difficulties in assessing changes in soil carbon storage over short time scales (<25 years; Prechtel et al., 2009). A second national monitoring programme called Countryside Survey has recently reported results from a similar time period indicating no evidence of topsoil carbon concentration or stock decrease at GB or individual country level (Carey et al., 2008; Reynolds et al., 2013). Other research has also suggested that woodland and grassland soils in particular may continue to sequester carbon for the foreseeable future, or at least not be losing their organic carbon (Freibauer et al., 2004; Soussana et al., 2007; Schils et al, 2008; Reijneveld et al., 2009). The only land use where it appears that there is general agreement that soils are losing organic carbon is on intensively cropped mineral arable soils (Freibauer et al., 2004; Carey et al. 2008). It has been suggested that climate change (increased atmospheric [CO_2] and temperature) may increase soil carbon storage by increasing net primary productivity (NPP) in vegetation and enhancing below ground inputs. Current evidence suggests that elevated CO_2 for example will induce carbon sequestration in agricultural and forest soils (Jastrow et al., 2005). However, the complex direct and indirect feedback loops that can occur also mean that it is difficult to predict how climate change will ultimately affect soil GHG emissions (Smith et al., 2008; Abdalla et al., 2013; Stavi and Lal, 2013). In this study we have therefore not taken account of changes in climate and atmospheric CO_2. Currently, the potential positive or negative impacts of climate change on soil carbon are not included in inventory calculations.

4. Inventory issues - Land use change options

From the outset it must be noted that the data presented within this report has an intrinsically high level of uncertainty. This is because the data used in our calculations have been derived from both field experiments and modelled data, many of which are not Wales, or even UK, based (Klumpp et al., 2009). Emissions from land are also known to be subject to large variations both spatially (i.e. within a single field as well as in the landscape; Souzanska et al., 2002) and temporally (i.e. through the day, season and year; Gibbons et al., 2006; MacDonald et al., 2007). This variability is particularly apparent for N_2O (Velthof et al., 2000). Furthermore, emissions from certain land uses have just not been measured, especially in Wales (e.g. under different grassland management regimes). Taking these statements together, it therefore remains difficult to derive robust ‘annual average’ values for GHG emissions (e.g. a forest may be a carbon sink in a dry year and a carbon source in the following colder year, whilst overall being a carbon sink; Chen et al., 2009). This is an important factor if we consider that an agri-environmental scheme (e.g. Glastir) typically has a life span of 10 years, whereas a change of land use from arable to woodland requires a time span of 100 years for soil carbon to achieve optimum levels although most change in ecosystem carbon storage tends to happen in the first 25 years. Therefore the data presented must be accepted as having a wide variation.

At present, LULUCF inventory is used to calculate the annual changes in CO_2 e associated with land use change in Wales. This uses a dynamic model to predict year-on-year changes in carbon storage/loss associated with land use change. In some cases the models are relatively complex (e.g. C-Flow for forest growth) and involve elements of product use whilst others rely on less sophisticated algorithms (e.g. arable → grassland). In addition, as it is not spatially explicit, there is no accounting for within land use management changes (e.g. re-seed of grassland → grassland) which may induce a considerable reduction in soil carbon storage. Similarly, LULUCF does not take account of policy instruments (e.g. agri-environment schemes) which may have significant changes in a land use (e.g. reduction in grazing density) and resultant changes in GHG emissions. In addition, the C-Flow model used in LULUCF assumes an increase in soil carbon with a change in land use to forestry; a feature that has not always been observed experimentally in the field and remains highly controversial (Hewitt et al., 2012).

Another fundamental issue associated with current inventories for carbon accounting in land use change calculations is the 'sectorisation' of the inventory base. For example, all N_2O and CH_4 emissions associated with agricultural (non-forest) systems are included in the Agricultural Inventory whilst those for forest systems are included in the Land Use,Land Use Change and Forestry Inventory (LULUCF). However, all changes associated with soil carbon stocks for all land uses are in the LULUCF inventory. Another anomaly is that while N_2O emissions from the agricultural use of fertilisers are accounted for in the Agricultural Inventory, the CO_2 e used in fertiliser production is embedded in the Energy Inventory and Fertiliser application in the Transport Inventory. Further, there is no accounting for indirect N_2O emissions arising from atmospheric nitrogen deposition (van der Gon and Bleeker, 2005). Finally, the direct fossil fuel substitution possible through burning wood is accounted for in the Energy Inventory and the indirect fossil fuel substitution through the use of timber instead of other materials such as concrete, steel and plastic is not accounted for at all.

Another issue that lends uncertainty to inventory calculations is the underpinning land use change data (i.e. land areas undergoing conversion) which is derived from 1990 Countryside Survey data. Overall, this dataset is perceived to be poor for capturing changes in land use in Wales due to its limited survey coverage.

It is important therefore that options to reduce GHG emissions in one sector do not merely result in increased GHG in another sector's inventory. For each option identified in this report there is a small section explaining if and where the GHG reductions would appear in the Greenhouse Gas inventory. In addition, some modifications of the current methodology or values are proposed together with the likely impact on current GHG emissions.

5. Assessment of options to reduce emissions

Actions have been identified from the scientific literature in an attempt to both reinforce the recommendations and quantify the benefit of adopting options for carbon sequestration as first proposed in 1994. Most recently these have been reviewed and summarised for Wales or Europe in the ECOSSE project report, Soussana et al. (2004), Freibauer et al. (2004), Smith et al. (2008), Levy et al. (2008), Dawson and Smith (2008) and Hillier et al. (2009). In reviewing the available literature it appears that although most scientists are agreed on the most appropriate GHG mitigation options, they disagree on either the magnitude of the response, the timescale in which it can happen, the area of land available to implement the option, and the socioeconomic potential for adoption. Some abatement options operate predominantly on one GHG (e.g. more efficient use of nitrogenous fertiliser to reduce N_2O losses), others on several (e.g. planting trees to reduce CO_2, N_2O and CH_4) whilst others involve trade-offs (e.g. ditch blocking in wetlands to capture CO_2 but increasing CH_4). In the recent review by Smith et al. (2008), in cool-moist regions such as Wales the highest mitigation potential for agricultural soils was identified as organic soil restoration which was a factor 5 to 10 times greater than any other option on an area basis. In this report, we review this within the context of additional reviews and Welsh data and indicate the land available and realistically available for each option. Many of the GHG mitigation options described here are highly soil type specific which prevents simplistic blanket recommendations being made.

6. Assessment of interventions

For each intervention option we carried out the following steps to determine the net change in GHG emissions that would occur whilst moving from one land use management regime to another. Year 1 was used at the point in which the land use intervention was imposed after which changes in soil carbon and GHG reductions were estimated over the subsequent 50 years:

(i) We collated values from published literature reviews which provided values for changes in GHG emissions and carbon storage for each intervention measure. Simultaneously, we matched these to land classes within the Welsh landscape.
(ii) We identified the mid-point value from (i) rather than returning to the primary literature which was not possible due to time constraints.
(iii) We adapted the midpoint value from (ii) for each soil type category.
(iv) We searched for Wales or UK intervention studies and modifying the midpoint from (iii) as appropriate.
(v) Using expert judgement we identified the temporal curves for the benefits to be realised (i.e. amount of C storage and GHG reduction after 1, 10, 30 and 50 years) for a range of potential uptakes by land managers (i.e. an adoption rate by farmers and land managers of 10, 30 or 50%).
(vi) Using expert judgement we then assessed the uncertainty for each option and assigned each option to one of four categories:
  a. early stages of development – too early to recommend
  b. contrasting results and/or lack of data – not recommended from current evidence base

c. some evidence in support which is supported by expert judgement but further research required before adoption
d. evidence base and expert judgement supports adoption

(v) We summarised all the options identified into the (c) or (d) categories in tabular and figure format.

6.1 Cropland interventions

Arable croplands only represent a small area of Wales (5.4% of the total land area). Of these croplands, at least 97% are associated with mineral soils. In many respects, these are the easiest land use to manage in terms of climate change mitigation as there is great amount of fundamental knowledge available on carbon sequestration and GHG emissions in a wide range of arable systems. In addition, mathematical models describing carbon and nitrogen cycling in these ecosystems are well developed allowing predictive simulations of land use and management change on GHG mitigation. Many management options are available for helping to reduce GHG emissions from Welsh croplands but ultimately the small land area means the overall potential for GHG emissions is relatively small compared to other options.

Potential management options considered for croplands include:

1. **Enhanced fertiliser management:** more efficient use of nitrogen based fertilisers, responsible for a large proportion of the GHG emissions from croplands (arising from fertiliser production, application, and direct N_2O emissions post-application; Hillier et al., 2009). In European agricultural systems typically 60% of the nitrogen applied is taken up by plants suggesting a high degree of wastage from leaching losses (as NO_3^- and dissolved organic N) and gaseous losses (as NH_3 and more importantly N_2O; Janzen et al., 2003). In GHG terms, nitrogen fertilizers have conflicting effects because they increase plant growth and therefore result in greater carbon inputs into the soil and replenishment of the soil organic matter pool. However, it is likely that this will be more than offset by the carbon involved in fertiliser production and subsequent N_2O emissions when applied to the soil (Schlesinger, 1999; King et al., 2004).
2. **Greater application of organic residues to land:** This depends on incorporating biological material produced from photosynthetic processes which take carbon dioxide out of the air and lock the carbon compounds in soil permanently (i.e. >50 years). Application of compost, digestate and recycled paper processing waste potentially offers GHG emissions savings through the diversion of materials from landfills – a major source of methane emissions. Also due to the nutrient delivery associated with applying green waste compost a reduction in synthetic fertilizers is achieved. However, evidence suggests that these only represent transient stores of carbon in soil unless continually replenished.
3. **Biochar addition to land:** Biochar (charcoal) is a variant of (2) above (Ameloot et al., 2013). It is produced from the pyrolysis of organic materials. If buried in soil it can act as a long term soil carbon store (>500 y). Although biochar could be produced on farm, the volumes of biomass available are

probably insufficient to meet demand. Therefore, it has been suggested that biochar could be produced from large volume waste materials (e.g. green waste, biosolids, forest residues) and subsequently ploughed into agricultural fields. Typical application rates of biochar to arable fields range 25 to 125 t CO_2 e/ha. After a few years of biochar amendment this would effectively double the amount of carbon stored in soil organic matter in the topsoil. Before adoption, however, full life-cycle analysis is required to quantify emissions associated with biochar production, transport and application together with implications for soil and water quality and long term food production (Mohd et al., 2013).

4. **Improvements in agronomy:** development of genetic breeding technologies including the selection for nitrogen use efficient cultivars (reducing the application rate of nitrogen fertilisers), and selection for deeper rooting crops that can sequester carbon deeper in the soil profile (Kell, 2011).
5. **Conversion:** This involves the permanent conversion of croplands to an alternative land use. All land uses, other than urban, store more carbon both above and below ground relative to cropland, so in all cases this would lead to a reduction in GHG. The obvious choices for Wales include a conversion to grassland or forestry but there would be the inevitable negative impact on food production.
6. **Larger field margins:** A relatively simple management option that could be implemented on Welsh croplands would be to increase the width of field margins around arable fields and/or to target low productivity areas within the field margins (Follain et al., 2007). This would result in an increase in soil carbon storage and an overall reduction in N_2O emissions as fertilisers would not be applied to these areas. This is particularly relevant as these areas are often compacted from repeated vehicle traffic and can be hotspots for N_2O emissions.
7. **Crop rotations:** A larger scale option is to increase fallow and crop rotations to increase the fertility potential of croplands (Aertsens et al., 2013). This should be based on the use of deep rooting crops which are not harvested but which recover nitrogen from depth in the soil profile and are subsequently ploughed in to return the nutrients back to the soil surface. Alternatively, N_2-fixing crops could be planted to enhance fertility (i.e. a move back towards the traditional rotation system). A significant gap exists in knowing the fluxes of N_2O from these N_2-fixing crops.
8. **Reduced tillage:** Tillage of soil (e.g. for weed control and seedbed preparation) impacts upon organic matter but is highly dependent on soil, type of cultivation, cropping system, manure management and climate (Bhogal et al., 2007). However, there is also a large controversy surrounding the use of no-till regimes for GHG mitigation. While there is no doubt that it enhances soil carbon storage, in contrast, it may increase N_2O emissions due to a greater amount of anaerobic hotspots in soil as a result of the increased bulk density. Overall, therefore GHG emissions may increase from reduced tillage practices as a result of increased emissions of N_2O.

In soil carbon terms, tillage has also been found to reduce the organic matter content of the top 5 cm by as much as 57% in comparison to conservation tillage (no ploughing or disc harrowing to 10 cm depth; Salinas-Garcia et al., 2002). Overall, tillage leads to a loss of soil carbon (Ogle et al., 2003). Impacts are also dependent on the type of cultivation carried out. The best estimate of carbon storage potential of zero tillage under England and Wales conditions is 1.1 (± 0.65) t CO_2 e/ha/y with reduced tillage having about half of this potential. These must be regarded as only the initial rate of increase (over less than 20 years), with a decline in the rate of carbon storage after this time. This accumulation process is finite. It is also reversible, if the practice is not continued permanently.

9. **Agroforestry and hedgerows:** Although planting trees in croplands (silvo-arable agroforestry systems) has the potential to enhance carbon storage, it is not favoured by farmers.
10. **Mineral addition:** Recent reports have suggested that crushed minerals could be used as a way of locking up inorganic carbon in soil (Manning, 2008). However, the technology is unproven and was not considered here.

The potential for cropland intervention measured for Wales is summarised below in Table 3 and Figure 2. Overall, it is obvious that the potential to offset GHG emissions has a finite lifespan or saturation limit with little capacity to reduce emissions further after 50 years if there is not additional uptake of options by land managers year on year. To a large extent this is due to the saturation of soil carbon pools. Overall, the most promising options for improved cropland management included a greater addition of organic residues to soil, enhanced fertiliser management, and the conversion of croplands to grassland. The incorporation of biochar into soil is a longer term option. As cropland only represents a small area of Wales the potential for emission savings are small unless the land is converted to permanent forestry.

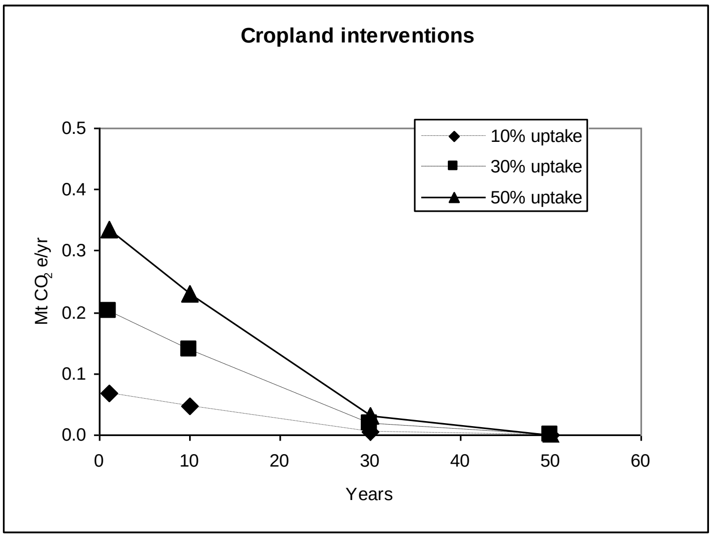

Figure 2. *Time course of greenhouse gas mitigation after the simultaneous implementation of a range of cropland intervention measures in Year 1 assuming either a 10, 30 or 50% adoption rate by farmers and landowners across Wales (but not including conversion to forestry or agroforestry which is considered elsewhere). Values represent the sum of all greenhouse gases (CO_2, CH_4 and N_2O) expressed as CO_2 equivalents per year. The three cropland intervention measures considered in the calculations include (1) enhanced fertiliser management, (2) conversion to grassland and (3) the increased addition of organic residues to cropland.*

Table 3. Estimated greenhouse gas reduction emission factor range (t CO_2 e/ha/y) on a per area for cropland based on literature values and midpoint adopted for Wales plus potential rates for Wales land area (kt CO_2 e/ y) at Year '10' and '30' assuming 10% uptake rates by farmers. Values represent the sum of all greenhouse gases (CO_2, CH_4 and N_2O) expressed as CO_2 equivalents per year.

Land use type	Intervention measure	Greenhouse gas emission midpoint (t CO_2 e/ha/y)	Greenhouse gas emission range (t CO_2 e/ha/y)	Potential annual GHG reduction (kt CO_2 e/ha/y)	
				Rate in Year 10 10% uptake	Rate in Year 30 10% uptake
Croplands	Enhanced fertiliser management	1	0.02-1.42	2	0
	Conversion to grassland	3	0.00-6.40	30	3
	Organic residues (composts, biosolids etc)	3	0.37-5.50	14	3
Longer term	Biochar addition	25	10 - 50	122	122
	Agronomy (better crops varieties etc)	1	0.51-1.45	0	3

6.2. Improved grassland interventions

Improved grasslands represent a large area of Wales (41% of the total land area). Of these, at least 96% are associated with mineral soils and 4% with organo-mineral soils. In many respects, improved grasslands are difficult to manage in terms of climate change mitigation as there is a fundamental lack of knowledge, or inconsistent results, about many of the potential mitigation options. In addition, mathematical models describing carbon and nitrogen cycling in these ecosystems are relatively poor in this context. It should also be noted that our knowledge of GHG emissions from these sites in Wales is relatively poor with only a few having been studied in detail. Consequently, the evidence presented here is subject to uncertainty.

For livestock systems, the proposed management options to reduce GHG emissions from grasslands in Wales include:

1. Reduced grazing
2. Improvements in agronomy
3. Improved fertiliser management
4. Greater application of organic residues to land

Other options considered here include biochar (charcoal) which has the potential to store waste-derived carbon in soil for hundreds of years and therefore act as a long term soil carbon store, but the best methods of incorporation into grassland have not been identified. It is likely that a one-off application could occur during reseeding where the biochar could be incorporated into the topsoil. The conversion of improved grasslands to forestry is considered later in this report.

The best strategies appear to be better management of organic wastes and reduced grazing. Biochar addition to soil represents a longer term strategy although the latter in subject to the availability of sufficient feedstock in Wales and major research before it could be recommended as an intervention measure. It is also apparent from the time course presented below that the time course of mitigation is maximal after 10 years but continued for at least 50 years.

Table 4. Estimated greenhouse gas reduction emission factor range (t CO_2 e/ha/y) on a per area for improved grasslands based on literature values and midpoint adopted for Wales plus potential rates for Wales land area (kt CO_2 e/ y) at year 10 and 30 assuming 10% uptake rates by farmers. Values represent the sum of all greenhouse gases (CO_2, CH_4 and N_2O) expressed as CO_2 equivalents per year.

Land use type	Intervention measure	Greenhouse gas emission midpoint (t CO_2 e/ha/y)	Greenhouse gas emission range (t CO_2 e/ha/y)	Potential annual GHG reduction (kt CO_2 e/ha/y) Rate in Year 10 10% uptake	Rate in Year 30 10% uptake
Improved Grasslands	Reduced grazing	2.8	0.18-5.50	79	8
	Enhanced fertiliser management	0.7	0.29-1.10	16	3
	Organic residues	2.9	0.37-5.5	112	22
Longer term	Biochar additon	55.0	10 - 100	364	364

6.3. Unimproved (semi-natural) grassland interventions

Unimproved grasslands (i.e. those not receiving fertilisers, lime etc) represent a relatively large area of Wales (32% of the total land area and 43% of all grasslands). Of these, 61% are associated with mineral soils, 33% with organo-mineral soils and 6% with peat soils. At present most unimproved grasslands in Europe are believed to be a sink for carbon (0.1-4.0 t CO_2 e/ha/y; Dawson et al., 2007). It should be noted, however, that our knowledge of GHG emissions from sites in Wales is relatively poor with only a few sites having been studied in detail. Consequently, the evidence presented here is subject to known and unknown uncertainty. The land use change options discussed here include:

1. **Reduced grazing:** The grazing density of sheep on unimproved grasslands has reduced in recent years (e.g. due to the implementation of agri-environment schemes). Current evidence on grazing intensity in the Welsh uplands suggests that reduced grazing results in either no change in soil carbon or a slight increase in carbon sequestration. This variability will depend on the initial grazing intensity and magnitude of the soil carbon store with respect to the maximum potential for soil carbon storage. There are two studies which suggest that light grazing may be optimal for soil carbon stocks (Bardgett et al., 2002; D. Jones Pers. Comm) and one study which identified no change between different grazing intensities (Emmett et al., 2007). Effects of grazing intensity on N_2O production are limited as emission rates from unimproved pastures are low anyway (Curtis et al., 2006). Direct emission of methane from animals would be additive to the reductions of those reported here if stocking levels were reduced and if there is no increase in animal numbers elsewhere to compensate.

2. **Agroforestry and hedgerows:** Planting trees and expanding hedgerows within upland grassland environments has some potential to store carbon in the long term and many other benefits for water, soil and biodiversity as indicated in the Pontbren project. However, preferably this should only be done on mineral or organo-mineral soils.
3. **Conversion:** This involves the permanent conversion of unimproved grasslands to forestry. As described above this can occur in a managed or unmanaged way. However, there are clear issues with respect to soil type for afforestation. Where possible organic peaty soils should be avoided as trees can dry out these naturally wet soils leading to a stimulation of soil organic matter loss through enhanced microbial action. There is also evidence to suggest that planting trees can stimulate the mining and loss of subsoil carbon in organo-mineral soils, although this can be offset by the increased sequestration of carbon in the above-ground biomass. As with most intervention measures, however, conversion to forestry has a finite lifespan in terms of carbon storage with maximal benefit seen in the forest 30 years after planting.

Overall, there are few relevant management options available for reducing GHG emissions from unimproved grasslands in Wales apart from conversion to forestry which is only practical and worth pursing in areas of Wales where organic soils are absent.

Table 5. Estimated greenhouse gas reduction emission factor range (t CO_2 e/ha/y) on a per area for semi-natural grasslands based on literature values and midpoint adoped to Wales plus potential rates for Wales land area (kt CO_2 e/ y) at year 10 and 30 assuming 10% uptake rates by farmers. The conversion of unimproved grasslands to forestry is considered later in this report.

Land use type	Intervention measure	Greenhouse gas emission midpoint (t CO_2 e/ha/y)	Greenhouse gas emission range (t CO_2 e/ha/y)	Potential annual GHG reduction (kt CO_2 e/ha/y)	
				Rate in Year 10 10% uptake	Rate in Year 30 10% uptake
Semi-natural grasslands	Reduced grazing	2.84	0.18-5.50	51	5
	Agroforestry/hedgerow	0.08	0.04 - 0.14	5	0

6.4. Bogs and fens

Bogs (upland nutrient poor peat soils) and fens (lowland nutrient rich soils) with free standing water only represent a relatively small area of Wales (1% of the total land area) as estimated by the Landcover map 2000 (LCM2000). This differs to estimates from other sources as areas containing bog-forming plants but not on soils characterised as peats will have been classified as acid grasslands i.e. LCM2000's distinction of bog, based upon mapped peat depth >0.5 m, does not include examples on shallow peat but with bog indicator species. Virgin peatlands (i.e. those not affected by excessive erosion, fire, climate change, grazing etc) take-up carbon at rates of 0.4-1.0 t CO_2 e/ha/y but emit CH_4 turning them into a source of 0.16 t CO_2 e/ha/r (range 0.14-1.5 t CO_2 e/ha/r) (Cannell and Milne, 1995). Many Welsh peats have become grass-dominated (esp. *Molinia*) and it's therefore questionable whether these peats are currently accumulating or not. In addition, there are areas of afforested peat that are almost certainly losing soil carbon, and areas with active peat erosion (C. Evans, Pers. Comm.). Apart from a manipulation of the drainage regime, only a few engineering-based management options are available for reducing GHG emissions from fens and bogs. Of these, the blocking of drains to induce permanent rewetting has gained considerable momentum in recent years. The long-term benefit (20-50 y) of this practice, however, is uncertain as there have been no published studies in Wales which have considered all the GHG simultaneously alongside measures of DOC, POC and DIC losses although several studies are now underway. Consequently, the evidence presented here is subject to uncertainty. The land use change options discussed here include:

1. **Rewetting peats:** Draining peat and lowering water tables has traditionally been carried out to prepare land for afforestation and agriculture, or for its extraction and use as fuel or in horticulture. Restoration by raising the water table and re-wetting peat, for example by blocking drainage ditches (often referred to as ‘grips’) is one potential option to restore the function of the peat as a net sink of CO_2 and a semi-permanent carbon store. However, the evidence-base concerning GHG emissions and carbon storage in peat in total after re-wetting however is poor as there are too few studies and those that exist are of low quality. In particular there is a major need to determine the long term rates of methane flux from both virgin, drained and rewetting peats in Wales. There is a greater amount of evidence on the effect of draining peat; however, the quality of most of these studies is similarly poor. The available evidence to date is consistent with this intervention mitigating climate change, at least to some degree, but better evidence is urgently needed. In the fens, reduced drainage may reduce productivity, increase the possibility of increased animal disease (foot rot), reduced accessibility (due to increased risk of mechanical damage from animals and machines), increase risk of runoff and reduce quality in water quality. In contrast, in the uplands reduced drainage should complement other ecosystem services by improving water quality (reduced DOC and POC) and enhancing biodiversity. However, it may negatively affect cultural activities (by reduced access). In conclusion, reducing drainage is a simple and cost-effective measure which could easily be implemented by land owners, particularly as it involves minimal intervention.

From Table 6 it can be seen that due to the small land area associated with bogs and fens in Wales (as recognised by CEH Land Cover Map 2000) the emission reduction is small in comparison to that achieved in some other land use sectors. However, without better scientific data these numbers should be treated with caution.

Table 6. Estimated greenhouse gas reduction emission factor range (t CO_2 e/ha/y) on a per area for bogs and fens based on literature values and midpoint adopted for Wales plus potential rates for Wales land area (kt CO_2 e/ y) at year 10 and 30 assuming 10% uptake rates by farmers.

Land use type	Intervention measure	Greenhouse gas emission midpoint (t CO_2 e/ha/y)	Greenhouse gas emission range (t CO_2 e/ha/y)	Potential annual GHG reduction (kt CO_2 e/ha/y) Rate in Year 10 10% uptake	Rate in Year 30 10% uptake
Bogs	Rewetting / restoration	27.2	-15.3 - 69.67	0.33	0.16

6.5. Forestry

Most Welsh woodland is either: (1) conifer woodland, mostly single-species, single-age plantations created during the twentieth century, which generally have been managed by clearfelling and are currently the main source of home-grown timber; or (2) native woodland, mostly small and fragmented, often on farms and much of it not actively managed. Not all native woodland is old, but a significant proportion has been continuously wooded for at least 400 years (including some that was more recently converted to non-native plantations). As forestry is generally a controlled operation it should be amenable to management to help prevent or offset GHG emissions in agriculture. Many forest management options are available including:

1. **Afforestation:** Planting trees locks up carbon from the atmosphere and may also increase the amount of carbon stored in litter and soil but this remains highly controversial. Currently, the LULUCF inventory uses data from the National Soil Inventory 1 m soil pits which assume a 30% increase in soil carbon following afforestation. There are conflicting results on the impacts of management on soil carbon, and it should be noted that most of the current carbon models lack appropriate validation, particularly for the below-ground components (Peltoniemi et al., 2007). Therefore, predictions made with such models should be treated with a high degree of caution. The C-FLOW model is currently used by CEH Edinburgh for the LULUCF Inventory to calculate impacts of afforestation on carbon stocks and fluxes both in the trees and soil. The uncertainty in C sequestration values and GHG emissions is likely to be a consequence of variability and uncertainty associated with soil types, thinning and harvesting practices, substitution issues and other underlying assumptions in the estimates. Our calculations to estimate GHG emission reductions have assumed reduced growth rates of trees and thus smaller emission reductions in unmanaged forestry relative to intensively managed forests.
2. **Increase rotation length:** It has been suggested that increasing rotation length from the current default of 59 years may provide a simple way of increasing carbon storage (Dewar and Cannell, 1992; Levy et al., 2008). This arises as essentially there is no decay associated with forestry products. In reality there is also potentially another benefit – that of reduced soil carbon losses as a result of soil disturbance associated with the extraction process resulting in decomposition of organic matter and erosion. However, it should

be noted these soil losses are not currently included in the LULUCF Inventory calculations. Furthermore, delaying felling in many Welsh conifer plantations may increase the risk of windthrow with all the resulting soil disturbance and potential higher decay associated with sub-optimally harvested wood products. There will also be trade-offs with socio-economic outputs associated with the forest industry for potentially very little carbon gain. A far better option in the medium-term is to manage a higher proportion of Welsh forests without clearfelling, ideally maintaining carbon stocks, reducing site impacts and maintaining a wood product flow.

3. **Site management:** One potential option is to prevent highly degrading practices such as stump removal, brash bailing and biomass burning and encourage minimum site preparation practices in Welsh forests. The disruption of the soil and removal of carbon inputs, post-harvest leads to a decline in soil carbon stocks. It should also be noted that site preparation can also lead to losses of soil carbon (estimated to be up to 30% by J. Morison, Forest Research), which may or may not be recovered over the subsequent decades of forest growth. The move to continuous cover forestry is perceived to have a small but positive impact on climate change mitigation. Where nutrients are added to forest sites these should be of a slow release nature (e.g. composts, pelleted wood ash) to prevent both losses by leaching and negative effects on soil quality (e.g. changes in pH and microbial activity or enhanced N_2O release). The potential reduction of these practices are still being determined.

Forestry offers excellent potential to enhance carbon sequestration in the Welsh landscape (Table 7, Figures 3-4). Current evidence suggests that most of this carbon will be stored in the trees rather than in the soil, particularly when trees are planted on improved grasslands. It should also be acknowledged that forestry may induce a loss of soil carbon, at least in the short term (<30 y; Hewitt et al., 2012). Changes in forest management (e.g. increased rotation length, better nutrient management, less site disturbance, lower impact harvesting operation) may significantly improve the carbon storage potential of forests but are of less significance than afforestation of grasslands and croplands.

Table 7. Estimated greenhouse gas reduction emission factor range (t CO_2 e/ha/y) on a per area for forests and afforestation based on literature values and midpoint adopted for Wales plus potential rates for Wales land area (kt CO_2 e/ y) at year 10 and 30 assuming 10% uptake rates by farmers. Forestry values include both GHG reductions associated with vegetation and soil. The calculations assume a 10% conversion of croplands, improved and unimproved grasslands to forestry in a managed (planted) and unmanaged (natural succession) way and the subsequent accrual of carbon in above and below ground vegetation and soil stores. No harvesting of the trees (and consequent substitution for fossil fuels etc) is assumed in the calculations. In addition, no planting is assumed on bogs and fens.

Land use type	Intervention measure	Greenhouse gas emission midpoint (t CO_2 e/ha/y)	Greenhouse gas emission range (t CO_2 e/ha/y)	Potential annual GHG reduction (kt CO_2 e/ha/y)	
				Rate in Year 10 10% uptake	Rate in Year 30 10% uptake
Forest	Increase rotation length	3.0	-6.1	9	27
	Afforestation (managed - all land cover types)	5.8	0.3 – 7.2	650	1300
	Afforestation (unmanaged - all land cover types)	5.8	0.3 – 7.2	192	640
Longer term	Biochar addition	25.0	10 - 100	38	113

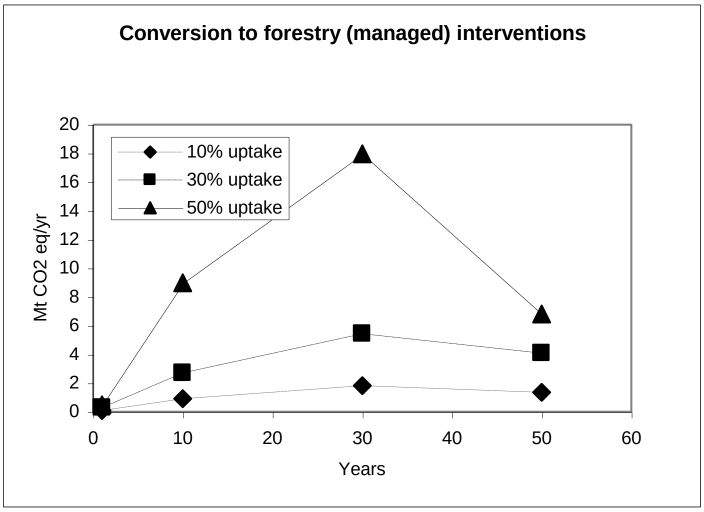

Figure 3 *Time course of greenhouse gas mitigation after the conversion of pasture and croplands to* ***managed forestry*** *in Wales assuming either a 10, 30 or 50% adoption rate by farmers and landowners across Wales. Values represent the sum of all greenhouse gases (CO_2, CH_4 and N_2O) expressed as CO_2 equivalents per year.*

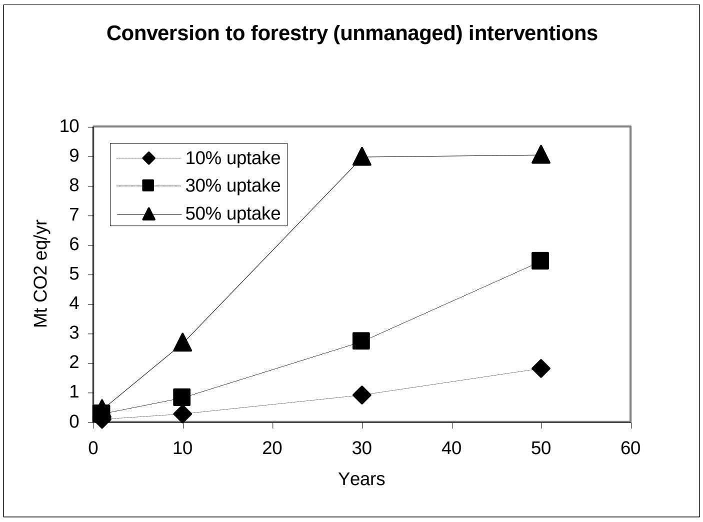

Figure 4 *Time course of greenhouse gas mitigation after the conversion of pasture and croplands to* ***unmanaged forestry*** *(i.e. natural succession) in Wales assuming either a 10, 30 or 50% adoption rate by farmers and landowners across Wales. Values represent the sum of all greenhouse gases (CO_2, CH_4 and N_2O) expressed as CO_2 equivalents per year.*

6.6. Overall analysis

In Figure 3 it is clear that the potential to reduce GHG emissions is maximal in the first 30 years but reaches quasi-saturation after 50 years. To put this into perspective, Figure 5 plots the sum of these GHG reduction measures against the 2005 baseline agricultural emission figures. Clearly, if these intervention measures are adopted they have the potential to make a difference. If we are looking for a 3% reduction in emissions each year relative to the 2005 baseline then we would be expecting a 30% reduction in 10 years. Figure 6 shows that this is clearly possible. After this point other mitigation measures would need to be devised if the targets are to be met. However, there are four issues which need to be highlighted:

(i) the current LULUCF inventory approach would not capture many of these changes and thus they would not be recognised

(ii) there is great uncertainty in one option which has one of the largest emission reductions i.e. biochar and it must be emphasised that this requires further research before recommending it as a viable option and

(iii) implementation of these land use measures will change the nature of the Welsh landscape from an aesthetic and cultural perspective. The direct costs (e.g. technology provision, manpower etc) and indirect costs (e.g. agricultural extension, potential effects on tourism) required to achieve these land use changes should not be underestimated.

(iv) The addition of organic residues to improved grassland is estimated to be a major mechanism of enhancing carbon storage in improved grasslands. However, where possible this waste should firstly be diverted to anaerobic digestion (with energy production) rather than applied directly to land.

It is important to recognise that there are three big uncertainties in our current understanding of the impact of changing land use to forestry.

- There are differences in estimates of GHG reduction reported here and those in Section 7 which reflect differences in assumptions made. Both approaches however support the significant carbon accumulation rates which accrue from afforestation. There is a need to improve dynamic forest carbon flow models (e.g. CSORT, CFLOW) to more accurately predict changes in soil and tree carbon stocks on different soils and with different management strategies.
- The assumption that forestry leads to a net accumulation of soil carbon deserves critical evaluation in the light of reports suggesting (i) no such gain when planted on improved agricultural grasslands, and (ii) losses from subsoil when trees are planted on upland (non-peat dominated) sites.
- Although not undertaken in Wales, the practice of stump harvesting should not be advocated for biomass recovery. Current evidence suggests that this practice could exacerbate soil carbon losses negating the carbon removed for biomass burning.

Table 8. Estimated greenhouse gas reduction emission factor range (t CO_2 e/ha/y) on a per area for all areas based on literature values, midpoint adopted for Wales plus potential rates for Wales land area (kt CO_2 e/ y) at year 10 and 30 assuming 10% uptake rates by farmers. Forestry values include both GHG reductions associated with vegetation and soil. Longer term options such as biochar application have been excluded.

Land use type	Intervention measure	Greenhouse gas emission midpoint (t CO_2 e/ha/y)	Greenhouse gas emission range (t CO_2 e/ha/y)	Potential annual GHG reduction (kt CO_2 e/ha/y)	
				Rate in Year 10 10% uptake	Rate in Year 30 10% uptake
All	All	26.9	-15.3 - 69.7	1159.6	2013.0

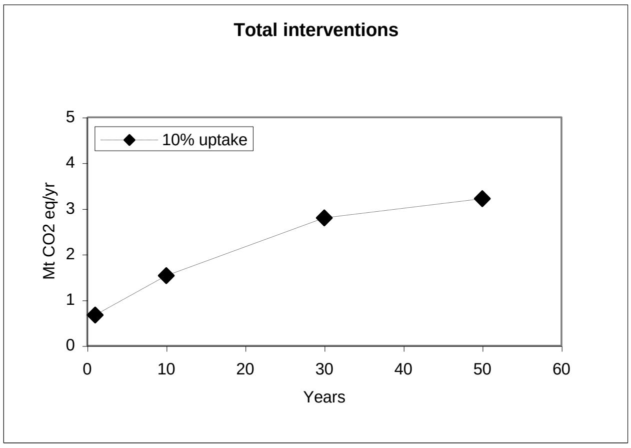

Figure 5. *Time course of total greenhouse gas reduction measures across Wales assuming a 10% adoption rate by farmers and landowners across Wales. Values represent the sum of all greenhouse gases (CO_2, CH_4 and N_2O) expressed as CO_2 equivalents per year.*

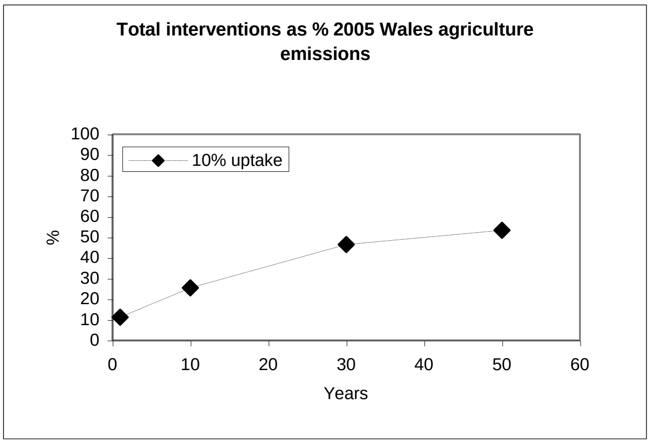

Figure 6. *Total impact of land use intervention measures on the reduction of greenhouse gas emissions across Wales as a percentage of the 2005 baseline agricultural emission figures.*

7. Key constraints and knowledge gaps and uncertainties

As noted earlier, the effect of land management practices and changes on emissions are far from being quantified. Further research is required to quantify the effects of grazing intensity and type, and the effects of land-use changes on combined emissions in soils and biomass. Research is also required on organic farm systems and minimum / zero tillage, due to the conflicting conclusions reached by recent studies. From the review undertaken here there is no doubt that there is great uncertainty regarding many of the values used in the mitigation model. This is due to the fragmented scientific evidence base for many land use types.

Models could be used but they need to be tested robustly. Current uncertainty using two current soil carbon models (RothC and Century) error was 5 -25 times Europe's emission reduction target. Experiments are needed using highly replicated plots of different management systems over time to test models. This would enable a separation of measurement vs modelled error.

Information pertaining to the impact of changing grassland management regime on GHG emissions remains scant with very few holistic studies undertaken in Wales or indeed globally. There is therefore a need to improve the knowledge base from a Wales-centric perspective; however, this must be done robustly. There is also a need for joined up thinking and trade-offs between GHG and other ecosystem services to be identified thereby removing us from a 'silo science' mentality. Research areas that urgently need attention include:

1. **Greenhouse gas budgets:** Most studies investigating the impact of land use change on GHG emissions remain only partially complete. This is because researchers have focused on measuring key components (e.g. soil CO_2 efflux from the soil surface) but have ignored losses of DOC or the lateral flow of N_2O and CO_2 (e.g. through sub-surface drains). Without these it is impossible to close the greenhouse gas budget. Further, few studies have actually been undertaken in Wales, and therefore by necessity, values used to predict the impact of land use change in Wales are derived from non-UK studies and as stated these are often incomplete. There is therefore a need to validate current estimates in a Welsh context or at least asses the level of uncertainty.
2. **Soil carbon stocks:** While we have good estimates of total soil carbon stores in Welsh soils (and vegetation), the impact of shifting from one land use to another (e.g. grassland to forestry) on soil carbon storage has great uncertainty, particularly in relation to soil type. Implicitly, the rate of change in soil carbon as a result of land use change has even greater uncertainty. Too many studies have emphasised the *potential* for carbon sequestration not the *likely* sequestration rates. They suggest in European croplands the only trend in agriculture that may be enhancing carbon stock on croplands at present is organic farming, and the magnitude is highly uncertain (Smith et al., 2005). The poor quality of this information has serious consequences for land use change models such as Ecosse whose outputs are heavily reliant on the quality of these input values. Estimates of soil carbon stocks under different land uses are also limited by sampling schemes that only survey topsoil (0-15 cm) or by assuming that soil

carbon content under different land uses indicate changes in sequestration rates. We recommend that a targeted field survey approach which explicitly addresses these problems is used to rectify this deficiency and development of the next generation of soils maps which are focussed on integration of soil parameters of functional importance.

3. **ECOSSE:** Ecosse-2 provides the best mathematical model currently available to predict the impact of land use change on climate change mitigation (SE, 2007; WAG, 2008). While the results from Ecosse-2 indicated the potential use of the models for landscape level predictions its current use is limited by the poor quality of soil and land use data at the correct spatial scales. We recommend that Ecosse is run for representative catchments using finer vegetation categories (split semi-natural vegetation categories) and obtained from different sources (e.g. Integrated Administration and Control System-IACS, Countryside Survey). Similarly the underpinning soil data should be used from contrasting sources (e.g. NRSI, CS, catchment-specific etc). The model also requires better estimates for vegetation net primary production to allow independent testing of changes in soil carbon sequestration rates. Greater knowledge of carbon losses during forest harvesting is also needed. Future expansion of Ecosse-2 should be to link the model with an LCA model that allows the whole ‘cradle to grave’ GHG emission values to be calculated (e.g. from transport, waste etc).
4. **N_2O emission factors:** There is uncertainty over the quality of fertiliser emission factors for N_2O in a Welsh context. Life cycle assessment models for agricultural systems rely on these factors and outputs from LCA for Welsh farming systems suggest that the outcome is critically dependent on these emission factor values. While values for arable systems are relatively robust, values for the dominant soil types/land use systems in Wales remain poor. These emission factors are also likely to be sensitive to future changes in climate, and in particular flooding and drought. Mathematical models used to describe N_2O fluxes at the national level are also poor and need improving if they are to be used as predictive tools (Abdalla et al., 2009).
5. **Fertilizer regime** With respect to nitrogen fertilisers, there is a need for better diagnostic testing so that farmers only apply nitrogen at the right amount and crucially at the time of maximum crop demand. A constraint to achieving this is the lack of a cost-effective farm-based diagnostic assay. This is compounded by the decline in soil testing undertaken by farmers to optimise their fertiliser application (due largely to economic constraints but also to a lack of faith in results). The impact of legumes as a replacement for inorganic fertilisers also needs critical evaluation from a GHG emission perspective (i.e. should we be moving towards organic-based farming systems).
6. **Grasslands:** Although re-seeding of lowland pastures is an important mechanism to improve productivity and reduce weeds the impact on GHG emissions remains unknown. Work needs to investigate the potential for optimizing this practice (time of year, plough depth, minimum-till potential etc). The potential to create new grass varieties that enhance carbon storage below ground is also possible (e.g. new high sugar yielding varieties)
7. **Peat re-wetting:** With respect to peat rewetting (“grip blocking”), there is a particular need for studies to address the flux of **all** greenhouse gases and dissolved-carbon losses simultaneously in the same locations so that the net global warming potential can be determined (i.e. all inputs and outputs required to complete a budget). Future large-scale re-wetting of peat should ensure that

these measurements are put in place urgently to ascertain whether this management intervention is having the planned net benefit for climate change mitigation. We recommend that an integrated experimental approach is used to address this at the catchment level.

8. **Tillage:** Although tilled land only accounts for a small proportion of Wales it is likely that changes in management regime will occur in the near and distant future as both technology and knowledge improves. In particular the use of no-till regimes is of interest as there have been conflicting reports about the relative merits of adopting it is a management strategy. The main uncertainty surrounds whether the increase in soil organic matter from reduced tillage is offset by the increase in N_2O emissions. Again, this highlights the need to calculate full GHG budgets for land management options.
9. **Land use change assessment:** Current estimates of land use change in Wales need significant refinement as they lack detail and fail to capture functional landscape details. More attention should be given to land use and land functions and linkages between these. Consideration of land functions that provide a wide range of goods and services will allow more integrated assessments of land change possible. New methods to map and quantify land function dynamics will enhance our ability to understand and model land system change and adequately inform policies and planning.
10. **Volatile organic carbon losses:** Emissions of VOC's from vegetation represent a small but important carbon loss pathway and are of similar magnitude as those for carbon leaving in freshwaters. Surprisingly, there are almost no values available for the UK, and of those, few relate to the impact of land use change on emissions. We recommend that an experimental approach is used to address this and that it should focus on grasslands where there is greatest uncertainty.

8. Constraints in implementation of recommendations

It is difficult to predict how future land use policies may interact with GHG mitigation measures. Whilst most should be complementary, others might not be (e.g. CAP reform; Water Framework Directive etc) and these should be considered in the early stages of GHG mitigation strategies.

Estimates for the realistic amount of carbon that can be sequestered in agricultural soils in Europe in the period 2008-2012 are believed to be less than one fifth of their potential and is equivalent to 2% of European emissions (Freibauer et al., 2004). There is also a need for: (i) permanent management change; (ii) implementation of concepts adjusted to local soil, climate and management features to allow for selection of areas with high sequestration potential. In addition the history of past policies can be informative (e.g. 1992 MacSharry set-aside reforms effectively prevented grassland to arable conversions by fixing the area of land that was eligible for arable area payments). In some areas of Europe, the Less Favoured Areas (LFA) policies have probably contributed to maintenance of permanent pasture but may have prevented return of land to natural vegetation which would have led to increase in vegetation carbon stocks but reduction in soil carbon stocks (Guo and Gifford, 2002 and Jackson et al., 2002) although this depends on soil type and natural vegetation cover.

Afforestation subsidies have increased carbon storage in vegetation, however, its impact on soil carbon stocks remains more controversial. Due to the uncertainty in response therefore, it may be more appropriate to reward a mitigation activity aimed at the increase in carbon rather than its actual effect since the latter may depend on climatic conditions beyond the farmer's influence. In summary the major constraints to achieving potential carbon sequestration rates in Wales includes:

- Lack of suitable or available land
- Lack of economic incentives
- Research and breeding for new crops still required
- Availability of manure and other organic wastes (e.g. especially if diverted to anaerobic digestion)
- Trade-off with food demand (biofuel / extensification can only use current setaside)
- Opposes current CAP policies (e.g. fertilising permanent pasture) and BAPs
- Limitation of soil type (i.e. peats)
- Traditional land management practice
- Needs practical demonstration to show it works
- Needs research to confirm findings

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