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Review of implications of land use change on climate change mitigation and adaptation

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1. Key Points

- Woodland expansion has potential to contribute to national GHG emission reduction targets, but care needs to be taken that trees are planted where they will not reduce the amount of land available for crop production, particularly as the changes in temperature and rainfall patterns are likely to result in an increased area of land available for agriculture.

- Peatland restoration has the potential to contribute significantly to meeting national GHG targets by allowing CO_2 to be sequestered from the atmosphere into the soil and vegetation. Due consideration must be give to initial methane release through rewetting, and further research is required into the effects of restoration of peatland degraded through conifer planting.

- Conversion of arable agriculture to pasture is likely to result in an increase of soil carbon in most cases, but may not lead to an overall net global warming benefit as this is dependent on what the pasture is used for. If it is used for sheep and beef cattle grazing, there is likely to be little net benefit as methane emissions will be largely offset by soil carbon sequestration. If used for dairying, methane emissions from the cows are likely to significantly outweigh any benefit from soil carbon sequestration. Buffer strips of grass and trees near to water courses, however, may contribute to adaptation to future climates through better flood management and biodiversity enhancement.

- Using land for production of renewable energy (e.g. wind farms, bioenergy crops) is likely in most cases to contribute to achieving GHG emission reduction targets. However, care needs to be taken that windfarms are not situated on pristine and deep peatlands due to the disturbance during construction releasing large quantities of CO_2 from the soil. Windfarms situated on degraded peatlands and on mineral soils are not likely to have the same effect. In the case of bioenergy crops, intensive production involving the use of fertilisers at high rates may offset any benefit from soil carbon sequestration and fossil fuel substitution.

2. Introduction

Climate change is widely recognised as the most serious environmental threat facing our planet today, and is becoming central to policy-making and land-use decision-making both nationally and internationally. Even though Scotland is only a small contributor to overall global GHG emissions, it is one of the higher per capita emitters, so the Scottish Government has accepted that it has a moral responsibility to demonstrate to the rest of the world that it can reduce its net emissions and move to a low-carbon economy in a sustainable way. As a result, the Climate Change (Scotland) Act was passed in 2009 committing the country to a target for reduction of GHG emissions of 42% by 2020 and 80% by 2050, targets that are amongst the highest in the world.

The 2009 Act included a requirement to produce a Land Use Strategy for achieving sustainable land use in Scotland, with revisions at five-year intervals. The first Strategy was submitted to the Scottish Parliament in March 2011, and is now in the process of being revised for resubmission in March 2016. Understanding how land use influences climate change and conversely how climate change influences land use choices is key to developing a revised strategy. This could be manifested in land use changes which act to mitigate climate change or strategic land use choices which enable adaptation to either the positive or negative aspects of climate change.

In this report, we collate recent research which examines aspects of land use change and how it contributes to climate change adaptation and mitigation, particularly in terms of interdisciplinary approaches, co-benefits, trade-offs and conflicts between different land uses, and which has the potential to inform strategic level decision making. The focus is on Scotland, but broader geographical contexts are considered where circumstances are applicable.

3. Approach

First, to provide a baseline, we review different land uses in relation to the amount of carbon stored in the soils and vegetation, together with information on the predicted greenhouse gas emissions from each land use. Second, we address the drivers of land use change and the implications that land use change will have on carbon storage and thus climate change adaptation and mitigation. We conclude by addressing the co-benefits, trade-offs and conflicts which may arise from future land use change in Scotland and indicate where further research is required to enable a robust land use strategy to be developed.

For the description of current land uses in terms of above and below-ground carbon stores and rates of greenhouse gas (GHG) emissions, we took the International Panel on Climate Change (IPCC) land use categories (cropland, forestland, grassland, wetland, settlements, and other) which are used as the basis for accounting in the UK Greenhouse gas inventory and the Land Use Land Use Change and Forestry (LULUCF) records on emissions and removals of greenhouse gases. We used these land use categories to enable comparisons with other studies. However, as these categories are very broad we have also identified the Joint Nature Conservation Committee (JNCC) broad habitat types (used for The Countryside Survey) which fall under each IPCC category, as in the Scottish context some broad habitats within an IPCC land use category are more likely to be subject to land use change than others.

For each IPCC land use category and sub-category baseline information on the soil carbon, vegetative carbon and greenhouse gas emissions (CO_2, CH_4, N_2O) have been collated where data is available. The values provided can be highly variable; this emphasises the importance of land management choices within a particular land use. In this review, however, we were asked to focus on land use change and not land management changes within a land use, as these are addressed in individual strategies such as the Scottish Forestry Strategy and Farming for a Better Climate. For example we address peatland restoration in the context of a land use change from forestry (afforested bog) to blanket bog, but aspects of peatland restoration such as adjusting grazing pressure and altering muirburn regimes are not addressed here as they are considered to be land management changes.

4. Land uses

Here we provide a summary of the above and below ground carbon stores, the greenhouse gas emissions and carbon footprint from each of the IPCC land use categories where data is available.

Croplands

IPCC Definition: Croplands are defined as arable crops such as cereals and vegetables, together with orchards, market gardening and commercial flower growing. In addition, freshly ploughed land, fallow areas, short-term set-aside and annual grass leys are included in this category (Webb *et al.,* 2014). In Scotland there are 534,000 ha of cropland covering 6.6% of the land area, which is mainly situated in the east of the country (Norton *et al.* 2009). The main crops are barley, wheat, oil seed rape, potatoes and oats, with smaller proportions of soft fruit production, and annual grass leys (Scottish Government, 2013a).

Above and below ground carbon storage: Scottish arable soils contain between 111.5 (± s.e. 15.6) and 150 t C ha^{-1} to a depth of 100 cm (Bradley *et al.,* 2005; Chapman *et al.,* 2013), with the greater proportion stored in the top-soil (120 t C ha^{-1}) while smaller quantities (40 t C ha^{-1}) are stored between 30 and 100 cm (Bradley *et al.,* 2005). Lilly & Baggaley (2013) also acknowledge the high carbon contents in Scottish top-soils and estimate Scottish cultivated mineral top-soils to contain a total of 246 ± 9 Mt C. However, this figure includes top-soils under both arable and improved grassland and therefore is best compared with Bradley's figure of 325 Mt C which includes soils under arable land and pasture. Bradley *et al., (*2005). give a higher estimate but they provide a combined figure for both organic and mineral soils to a depth of 30cm which incorporates the topsoil and some of the subsoil; in contrast Lilly & Baggaley (2013) focus on 'true' mineral top-soils to a mean depth of 27 cm.

In comparison, above ground carbon stocks (comprising stems/foliage) are small, with maximum values reaching 1.5 t C ha^{-1} (Webb *et al.,* 2014). However, Milne & Brown (1997) provide a lower value of 1 t C ha^{-1} for land under cereal or horticultural crops but also recognise that during fallow periods no above ground carbon storage is provided.

Greenhouse gas emissions and carbon footprint: Greenhouse gas emissions from cropland calculated from the 2011 LULUCF emissions and removals of greenhouse gases supporting dataset are estimated to be 3.09 t CO_2e ha^{-1} (Malcolm *et al.*, 2013). However, it should be noted that this value does not take into consideration emissions produced from farm machinery, as these are accounted for out with this land use sector. Hillier *et al.* (2009a) recognise the variety of crops grown and the type of farming system (i.e. organic, conventional or integrated) has a large influence on the carbon footprint of arable production. The mean carbon footprint across all crop types is estimated to be 1.29 t CO_2e ha^{-1} yr^{-1} (Hillier *et al.,* 2009a). Yet this can range from 0.07 t CO_2e ha^{-1} yr^{-1} for *Phacelia* (grown as a set-aside crop) to 3.31 tCO_2e ha^{-1} yr^{-1} for spring barley where inputs of inorganic fertiliser and farmyard manure have been used. Organic arable farming systems tend to have a lower carbon footprint (0.76 t CO_2e ha^{-1} yr^{-1}) compared to conventional systems (1.64 t CO_2e ha^{-1} yr^{-1}) and the intermediate integrated systems (1.26 t CO_2e ha^{-1} yr^{-1}). This is connected to the amount of nitrogen fertiliser applied to the land. Organic farming systems rely more heavily on Farm yard manure (FYM) compared to inorganic nitrogen fertiliser and generally apply less Nitrogen per unit area i.e. N applied as FYM = 75kg/ha (range 12-194kg/ha) compared to N applied as inorganic N fertiliser = 120kg/ha range(12-230kg/ha (Hillier *et al.,* 2009a). Organic farming systems also make more use of nitrogen fixing legumes than conventional farming systems. Integrated farming systems lay somewhere in between. This is likely to be due to the careful planning of where N-inputs are required so that waste is minimised.

Grasslands

IPCC Definition: Grasslands include improved, neutral, calcareous and acid grassland together with bracken, dwarf shrub heath, fen/marsh/swamp, bogs and montane habitats. In these areas grazing is the pre-dominant land use; therefore areas of wetland habitat which are not used for peat extraction, such as bogs, are also included in this category (Webb *et al.,* 2014). In Scotland, bog makes up the largest proportion of this category representing about 26% of Scotland's land area, followed by acid grassland 12% and dwarf shrub heath and improved grassland each covering about 11% of the land area (Table 1) (Norton *et al.*, 2009). Bog, dwarf shrub heath and acid grassland tend to be confined to higher elevations and the land is predominately used for extensive grazing, deer stalking, grouse shooting and other recreational pursuits such as hill walking. In contrast improved grassland tends to be confined to lower areas in the south and east of the country.

Table 1: Data from the countryside survey 2007 (Norton *et al.,* 2009)

Broad habitat type	Area (Kha)	% area of Scotland
Improved Grassland	907	11.2
Neutral Grassland	461	5.8
Calcareous Grassland	26	0.3
Acid Grassland	983	12.3
Bracken	131	1.6
Dwarf shrub heath	894	11.1
Fen, Marsh, Swamp	238	3
Bog	2044	25.6
Montane	38	0.5

Above and below ground carbon storage: As the IPCC grassland category is broad, estimates of carbon storage drawn from the literature may only encompass sub-categories. For semi-natural land, which is likely to incorporate all the broad habitat types listed in Table 1 apart from improved grassland (i.e. 60.2% of Scotland's land cover), a soil carbon store of 330 t C ha^{-1} is given by Bradley et al. (2005), this takes account of carbon stores down to 100 cm – values for 0-30 cm are given as 160 t C ha^{-1}, and for 30-100 cm, 170 t C ha^{-1}.

Chapman et al. (2013) provide separate values for improved grassland, semi-natural grassland, moorland and bog to a depth of 100cm. Bog stores the most carbon (528.3 ± 23.0 t C ha^{-1}) followed by moorland (290.8 ± 26.3 t C ha^{-1}) and then semi-natural grassland (185 ± 27.1 t C ha^{-1}) with improved grassland storing the least (138.1 ± 21.4 t C ha^{-1}). It should be recognised that these values have some uncertainty surrounding them due to the variability in the soils. This is particularly important when considering the carbon storage capacity of bog which comprises almost 26% of Scotland's land cover.

The soil carbon storage of bog has been expressed by many authors on a national basis i.e. the whole of Scotland and as such a value of 904 Mt of carbon to a depth of 1m has been given for organic soils by Bradley *et al.* (2005), with 274 Mt of this contained in the first 30 cm and a further 630 Mt between 30-100 cm. However, peat depth frequently exceeds 1 m and indeed Milne & Brown (1997) provide an estimated total carbon store of 4523 ± 2287 Mt to 1 m depth, with another 3248 Mt stored below 1 m (Milne et al., 2001). However, there is approximately a 50% error in this value due to variability in soil bulk density and uncertainty in the estimation of peat depth (Milne & Brown, 1997). Chapman *et al.* (2009) managed to reduce this error by including better information on peat depths and estimated peatland carbon storage at a lower value of 1620 ± 70 Mt, which nevertheless still represents a substantial carbon store comprising 56% of all carbon in Scottish soils (Chapman *et al.,* 2009).

As expected, carbon stored in grassland vegetation (above ground carbon) is very small compared to that in the soil and is given as 0.18 t C ha^{-1} by Webb *et al.* (2014), whilst Milne & Brown (1997) provide a value of 1 t C ha^{-1} for pasture and unimproved pasture and a value of 2 t C ha^{-1} for shrubs, heath and bog. All values are low but it does demonstrate the range of values which can be obtained when looking at such a broad land use category.

Greenhouse gas emissions: Greenhouse gas emissions from grassland calculated from the 2011 LULUCF emissions and removals of greenhouse gases supporting dataset are estimated to be -0.40 tCO_2e ha^{-1} yr^{-1}, i.e. grasslands contribute to a reduction in greenhouse gas emissions (Malcolm *et al.,* 2013). However, as previously discussed the grassland category is very broad and thus there is likely to be a lot of variability surrounding this value. For example, improved grasslands generally receive inputs of nitrogen fertiliser potentially leading to nitrous oxide emissions (N_2O has 298 times the global warning potential of CO_2), whereas semi-natural grasslands, heathlands and bog do not receive these inputs. Furthermore, if a more holistic approach is taken and methane emissions from livestock grazing on the grasslands are also included in this calculation (emissions from enteric fermentation are accounted for under the agricultural sector for the purposes of the UK

GHG inventory), the value would be even higher (CH_4 has 25 times the global warning potential of CO_2).

Forestlands

IPCC Definition: Forestlands are areas of land under stands of trees which form at least a 20% canopy cover (or have the potential to achieve this). Felled areas ready for restocking are also included in this category (Webb *et al.,* 2014). Woodland makes up 15% of Scotland's land cover, the vast majority of this area (11.9%) consisting of coniferous woodland with broadleaved woodland making up the remaining 3.1% (Norton *et al.*, 2009).

Above and below ground carbon storage: Soil carbon in woodland soils has been estimated as 267.5 ± 40.5 tC ha^{-1} (or 186.7 ±26.9 tC ha^{-1} if woodlands on deep peat are excluded) by Chapman *et al.,* (2013) and 330 tC ha^{-1} by Bradley *et al.* (2005) up to a depth of 1 m, with equal amounts of carbon (170 t ha^{-1}) stored in the first 30 cm and between 30-100cm (Bradley *et al.,* 2005).

In contrast to the other land use categories, above ground carbon stocks (comprising stems, branches and foliage) can be large and are dependent on the age and species of tree, with younger (smaller) trees storing less carbon than mature (larger) trees and with broadleaved trees generally storing more carbon than conifers(Conifer: age class 0-10yr = 4.8 t ha^{-1}, age class >120yr 69.1 tC ha^{-1}; Broadleaf: age class 0-10yrs = 5.7 tC ha^{-1}, age class >120yrs = 98.9 tC ha^{-1} , values for individual species are provided by Milne & Brown (1997)). In fact, more carbon is sequestered in the biomass of trees grown for amenity purposes, such as parkland trees, compared to those in plantations grown for timber (Cannell, 1999). This is because amenity trees are allowed to grow to maturity whilst plantations are felled earlier. Amenity trees are also often broadleaved trees which have denser timber and thus store more carbon. However, generally the planting density of trees will be higher in a plantation compared to amenity woodland thus providing greater carbon storage per unit ground area.

When comparing the amount of carbon stored in soils (Bradley *et al.,* 2005) relative to forest biomass (Milne & Brown, 1997), forest soils contain more carbon than the vegetation component, a finding consistent with preliminary analysis of data from Forestry Commission forests in Scotland (Gimona, pers. comm.)

Greenhouse gas emissions: GHG emissions from forestland calculated from the 2011 LULUCF emissions and removals of greenhouse gases supporting dataset are estimated to be -4.81 tCO_2e ha^{-1} yr^{-1} (Malcolm *et al.,* 2013), indicating their potential to reduce overall GHG emissions. However, the end product form the forest should also be taken into account – long-lived timber products will keep carbon 'locked' up for longer, whilst production for short cycle markets such as paper act as a temporary carbon sink.

Wetlands

IPCC Definition: Wetlands include any land that is covered or saturated by water for all or part of the year which does not fall into the Forest Land, Cropland, or Grassland categories. It includes peatlands managed for peat extraction (Webb *et al.,* 2014).

It is difficult to tease this category out from the Scottish Countryside Survey dataset as fen, marsh and swamp are included in the grassland category and all peatlands, whether currently managed for peat extraction of not, are recorded under the bog category. However, these habitats are only a small proportion for the land area (fen, marsh, swamp = 3%) (Norton *et al.,* 2009) and commercial peat extraction has been greatly reduced, therefore these habitats are addressed in the grassland category.

Settlements

IPCC Definition: Settlements include both urban and rural settlements, farm buildings, caravan parks and other man-made built structures such as industrial estates, retail parks, waste and derelict ground, urban parkland and urban transport infrastructure. It also includes domestic gardens and allotments, boundary and linear features, such as hedgerows, walls, stone and earth banks, grass strips and dry ditches. Some built components of the rural landscape including roads, tracks and railways and their associated narrow verges of semi-natural habitat are also included in this category (Webb *et al.,* 2014).

The Countryside Survey data for Scotland identifies 1.9% (153,000 ha) as built up areas and gardens, a further 0.5% (38,000 ha) as un-surveyed urban land, and 1.2% (95,000 ha) as boundary and linear features (Norton *et al.,* 2009).

Above and below ground carbon storage: Little data is available for the carbon content of soils below settlements, but values are likely to vary widely depending on the historic use of the land and how much topsoil is removed in the development process. Bradley *et al.*, (2005) assume a value of 0 t ha^{-1} for land that has been built over in urban areas, and that soils built over in suburban areas contain half as much carbon as that found under pasture, while garden soils contain 90 tC ha^{-1} to a depth of 1 m with the majority of carbon being stored in the top 30 cm of soil (70 tC ha^{-1}) and a smaller quantity (20 tC ha^{-1}) at 30-100 cm.

The above ground carbon storage is influenced by the type of vegetation within a settlement or the specific materials used in a building, for this reason is likely to have a wide range of values. However, Webb et al. (2014) provides a general figure of 0.29 tC ha^{-1}.

Greenhouse gas emissions: GHG emissions from settlements calculated from the 2011 LULUCF emissions and removals of greenhouse gases supporting are estimated to be +4.37 tCO_2e ha^{-1} yr^{-1} i.e. they are a net contributor to GHG emissions (Malcolm *et al.,* 2013).

Other

IPCC Definition: Inland rock, standing water, canals, rivers and streams all fall into the other category (Webb et al., 2014). In Scotland standing open water, canals, rivers and streams comprise 1.4% of the land area and 1% is covered by inland rock (Norton *et al.,* 2009).

Above and below ground carbon storage: Little data is available, but stored carbon is likely to be zero or negligible. Milne & Brown (1997) do provide a value of 2 tC ha^{-1} for maritime vegetation, however this is technically not a land based vegetation community and thus beyond the scope of this review on land use change.

Greenhouse gas emissions: No data is available.

Summary of land uses

When comparing all the IPCC land use categories, grassland soils tend to store the most carbon. However, this is an oversimplification as soil carbon contents vary widely depending on the type of grassland in question and are likely to be a product of the soil type and the level of disturbance that the soil receives or has received in the past. Bog, comprised of rich organic soils (peat) with a high water holding capacity, provides the highest carbon storage in its undisturbed state; whereas moorland and semi-natural grassland have lower soil carbon contents. These vegetation types will have been subject to low levels of disturbance (grazing/trampling by wild animals and livestock and habitat management such as muirburn) leading to a lower level of organic matter accumulation and greater exposure of the soil surface which in turn causes carbon loss through oxidation. Improved grassland will have experienced the highest level of disturbance, through ploughing, drainage, re-seeding and grazing and thus exhibits the lowest soil carbon content due to low levels of organic matter accumulation and loss of existing soil carbon through oxidation and soil erosion. However forest soils also contain high levels of soil carbon. This can be attributed, in part, to many plantations being established on peat in upland regions but also to the long period (length of the rotation) when the soils are left undisturbed and organic matter (from leaf fall and deadwood) can accumulate on the forest floor. In contrast, cropland, like improved grassland, has low levels of soil carbon storage due to the high level of soil disturbance.

The above ground carbon storage also differs between land uses. The highest storage levels are provided by forestland where a large proportion of above ground biomass is sustained over a long period of time. Smaller quantities are found in grasslands and croplands. However in the latter, arable crops are harvested annually and therefore don't offer the long-term carbon storage potential of grasslands.

Furthermore, carbon storage in soils is much greater than that sequestered in biomass (Milne & Brown, 1997). However, both the above and below ground carbon stores, combined with the management of the land, such as the inputs required, i.e. nitrogen fertilisers, contribute to the equivalent GHG emissions produced from a particular land use. Data provided in the Land Use Land Use Change and Forestry (LULUCF) emissions and removals of greenhouse gases report for Scotland show settlements, cropland and wetlands to be net greenhouse gas emitters, whereas forestlands, and to a lesser extent grasslands, help to sequester carbon and thus lead to a reduction in GHG emissions (Figure 1).

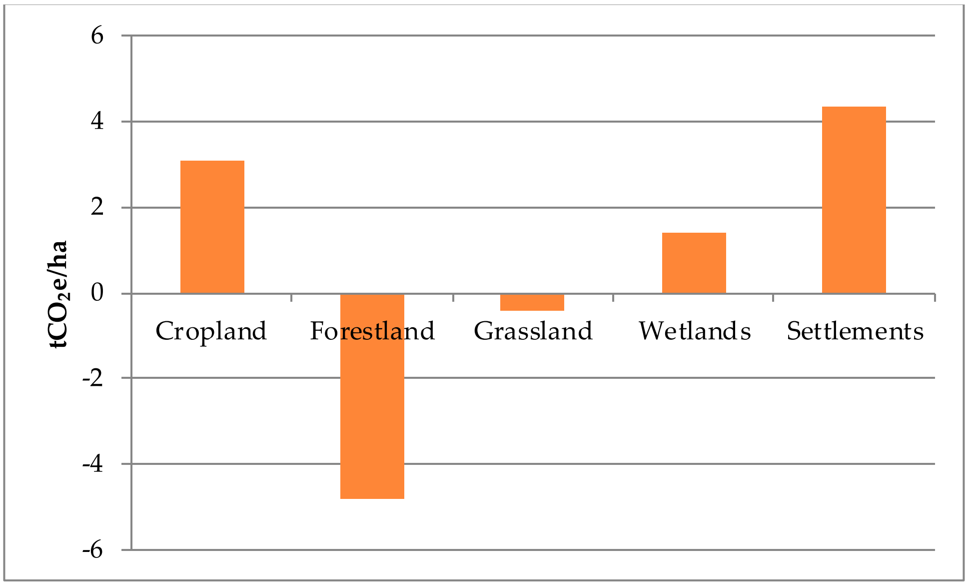

Figure 1: Greenhouse gas emissions expressed as tCO_2e ha^{-1} for each land use category. Figures based on emissions data and land areas from the 2011 LULUCF emissions and removals of greenhouse gases supporting dataset.

5. Land use change

Having summarised details of the baseline carbon storage and GHG emissions from different land use categories, we now turn to the impact of land use change on these. We first identify some of the drivers of land use change, and then look in detail at the implications of land use changes for climate change.

Drivers of land use change

Land use change can be influenced by many factors, including technological advancements, social attitudes, economics, land tenure, land quality, existing policies and regulations as well as climate change (Rounsevell & Reay, 2009; Sutherland *et al.,* 2011; Kyle *et al.,* 2014; Birnie & Mather, 2006; Gimona *et al.*, 2012). However, it must be recognised that these drivers are not mutually exclusive. Furthermore, while some factors may help to drive land use change, others may act to maintain the *status quo*. For example, advancements in renewable energy technologies could lead to increases in the land area planted for biofuel production, while grants for woodland creation could provide a financial incentive for planting more trees, or a global demand for food production could lead to an increase in arable farming. Similarly, 'social norms' (culture, traditions and peer pressure) may also influence land use decisions (Kyle *et al.,* 2014). This may act to maintain the *status quo*. It should also be recognised that land managers may be more willing to commit to a land use change which can be easily reversed rather than one which has permanent or long lasting consequences (Kyle *et al.,* 2014). Furthermore, the length of land tenure is also likely to influence future land use decisions (Kyle *et al.,* 2014; Birnie & Mather, 2006), particularly where a proposed land use change requires substantial capital to bring about the change and where the payback time is long. Rounsevell & Reay (2009) conclude that socio-economic and technological changes are likely to be the most important drivers for land use change, while Sutherland *et al.* (2011) show that a concern for society, and the benefits that any land use change may have on a community, are important factors in land use decision making.

In a Scottish context a key mechanism for delivering a reduction in GHG emissions is the Report on Proposals and Policies (RPP), the second edition of which was published in 2013 (Scottish Government, 2013b) in which rural land use is identified as one of six main sectors. This together with various other strategies and policies, including the Scottish Forestry Strategy (2006), the Rationale for Woodland Expansion (2009), the Scottish Soil Framework (2009), Farming for a Better Climate (2010), the Draft National Peatland Plan (2011), the National Planning Framework 3 (2014), and Climate Ready Scotland (2014) have the potential to influence land-use decision making and therefore drive land-use change in Scotland with the aim of reducing GHG emissions.

Land use change and carbon storage

Reviews by Guo & Gifford (2002)and Dawson & Smith (2007) identify the changes in soil carbon storage when land is converted from one land use to another (see Appendix I) . However, few of the studies which they review relate specifically to Scotland or the UK. Yet many of the findings reflect changes to the baseline carbon stores detailed above, and are consistent with the changes in carbon storage between land uses provided in the UK Greenhouse Gas Inventory (2014). In general, soil carbon stocks are highest under forestland, followed by grassland, cropland, wetland, settlements and 'other'. Broadly speaking, these differences are due to the differences in carbon inputs to the soil from the vegetation (i.e. leaf litter, woody litter and rhizodeposition), and outputs from the soil due to microbial respiration, erosion and percolation. Any change in land use results in a change in these inputs and outputs of carbon such that a new equilibrium is reached. In general, a move from a land use with higher soil carbon stocks to one with lower carbon stocks will result in the loss of carbon, much of which will be to the atmosphere in the form of CO_2 produced by microbial respiration.

Thus, when forestland is converted to grassland, croplands or settlements, soil carbon stores are generally expected to reduce, with the greatest reduction occurring when forestlands are converted to settlements, closely followed by croplands, and to a lesser extent grasslands. Where grasslands are the original land use, soil carbon storage can usually be increased by planting trees, while where croplands are the original land use, gains can be made when converting to forestland or grassland, but reductions are made when converting to settlements. The greatest improvements in soil carbon storage can be gained by converting settlements to forestland, grassland and cropland respectively Figure 1).

In terms of biomass carbon stores, forestlands are the land use providing the highest above ground carbon storage. A change to any other land use will lead to carbon loss and conversely a change from grassland, cropland or settlement to forestland will lead to an increase in carbon storage. Biomass carbon gains and losses occurring as a result of transitions between cropland, grassland and settlements are very small. However, converting grassland to crops will lead to a small loss of above ground carbon, while converting to settlements will increase the carbon stored and changing cropland to either grassland or settlements will lead to net carbon gains, whereas changing settlements to croplands or grassland will lead to net carbon losses (Figure 3.).

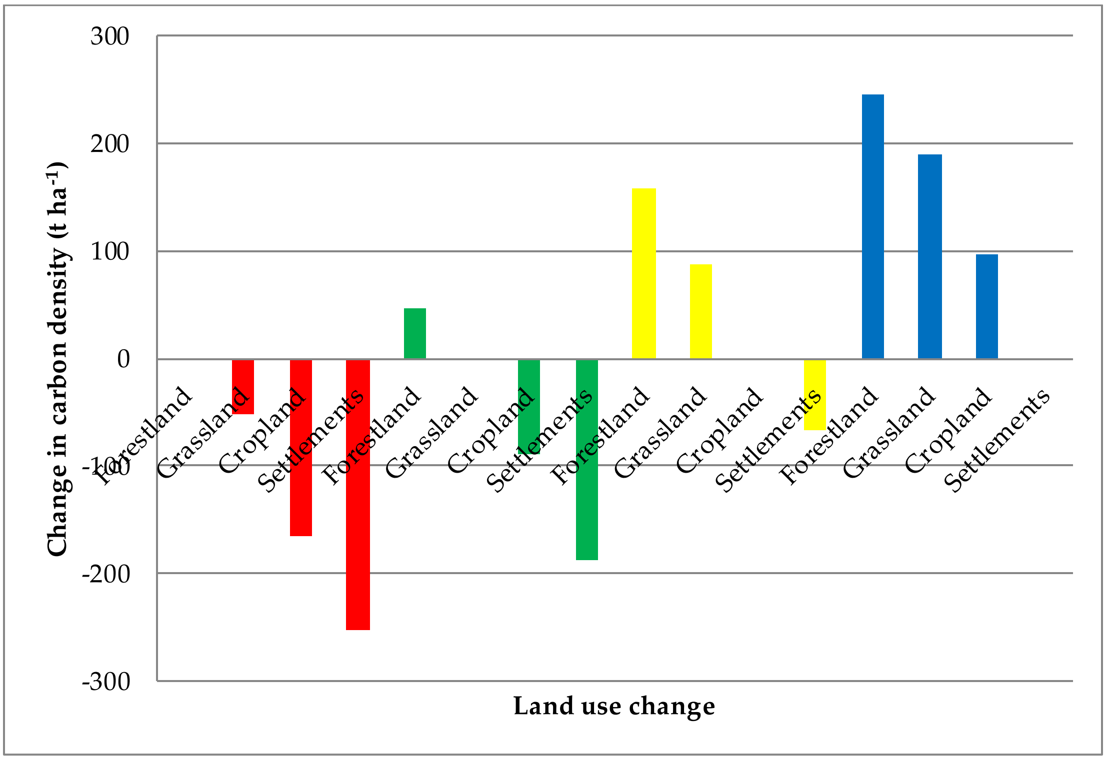

Figure 2: Below ground carbon stocks following land use change. Each colour represents one set of possible land use transitions. The land use with a value of zero is the original land use (red: forestland; green: grassland; yellow: cropland; blue: settlements) and carbon gains and losses are shown when the land use moves to another category. Figure based on data from the Annex 3.6 of the UK Greenhouse gas inventory (2014).

However the amount of carbon stored, particularly in the soil, is highly dependent on the soil type and land management and it should be recognised that carbon stores for a particular land use encompass a wide range of values. Existing land management should therefore be taken into consideration when calculating the potential benefits of moving to another land use.

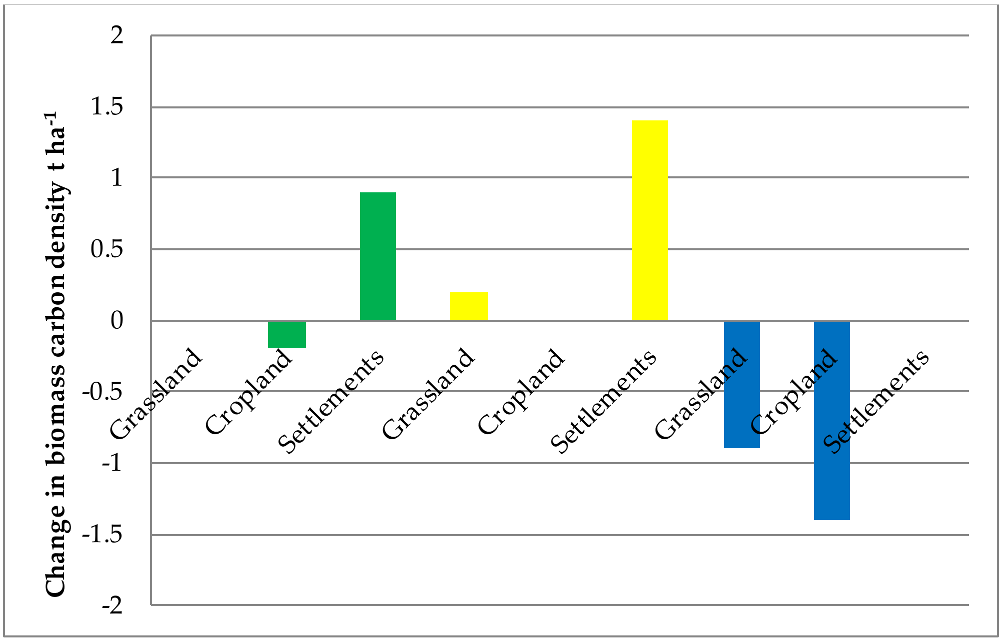

Figure 3: Above ground carbon stocks following land use change. Each colour represents one set of possible land use transitions. The land use with a value of zero is the original land use (green: grassland; yellow: cropland; blue: settlements) and carbon gains and losses are shown when the land use moves to another category. Figure based on data from the Annex 3.6 of the UK Greenhouse gas inventory (2014).

The rate of soil carbon change can vary between different land use transitions. However, little data is available to address this in a Scottish context, and indeed when looking at the UK as a whole. Chapman *et al.,* (2013) compared carbon stocks in Scottish soils between 1978 and 2009 but had insufficient sites where there had been a land use change to determine the effect of that change on soil carbon stocks. Likewise , Bellamy *et al.* (2005) conducted a similar study in England and Wales but also had insufficient soil data corresponding to land use changes to explore the rate of soil carbon change with land use change. However, generally, losses of carbon from one land use to another are relatively fast whereas gains are relatively slow (Table 2.). The figures provided in the UK greenhouse gas inventory are given as 50-150 years for 99% of a fast change to occur, while 300-750 years is given for 99% of a slow change to occur (Webb *et al.,* 2014). The origin of these figures is not clear and it might be expected that soil carbon losses may occur much more rapidly than this due to land use changes, for example when forestland is converted to grassland, cropland or settle ment or when grassland is converted to cropland or settlement. However, further research is required.

Table 2: Rate of change of soil carbon for land use transitions (Webb *et al.,* 2014)

		Initial			
		Forestland	**Grassland**	**Cropland**	**Settlement**
Final	**Forestland**		*Slow*	*Slow*	*Slow*
	Grassland	*Fast*		*Slow*	*Slow*
	Cropland	*Fast*	*Fast*		*Slow*
	Settlement	*Fast*	*Fast*	*Fast*	

Adaptation and land use change

The relationship between land use change and adaptation can be conveniently divided into two broad categories – (a) the impact of adaptation by humans to future climates on land use change, and (b) the influence of land use change on adaptation of organisms to future climates. Examples of the first of these include changing land use to improve flood control made necessary by increased rainfall and sea-level rise in some places (both in relation to averages and extreme events), and changing land use in response to changes in land suitability for different purposes, such as agriculture or forestry. Examples of the second include the impact of these and other land use changes on the ability of non-human organisms to adapt to future climates – increase in woodland extent, for example, may enable many species to migrate northwards through provision of habitat networks. Different species dependent on different land uses for habitats may migrate at different rates, which will have implications for predator-prey relationships.

However, there are several factors influencing adaptation of humans in the future in addition to climate change. Probably the most influential is economics – the relative profitability of different land uses driven by relative commodity prices and/or economic instruments such as taxes or incentives. It is often difficult to predict these – who for example foresaw the rapid decline in oil price in 2014? – or even the impact of these once they do happen – e.g. the jury is still out on whether fossil fuel use will increase due to the low price stimulating demand, or whether it will decrease due to it reducing supply from uneconomic oilfields. Economic volatility also is important – to reduce risk from extreme events (both economic and biophysical), land managers may wish to diversify their land use, regardless of which are the economically optimum options.

With this in mind we now explore potential land use changes in Scotland and address the consequences of each land use change on climate mitigation and adaptation.

Impacts of specific land use changes

In the context of the RPP2 (Scottish Government, 2013b) and the Scottish Climate Change Adaptation Programme (SCCAP), we now discuss some of the potential land use changes in Scotland and assess the consequences for climate change mitigation and adaptation. A summary of the mitigation and adaptation effects and the conflicts which may occur from land use change is provided in Table 3.

Woodland expansion

Increasing forestland leads to greater carbon sequestration, both in the soil and the biomass, and can therefore help to mitigate climate change by reducing net GHG emissions. With this in mind a target to increase the woodland cover by 10,000 ha per year has been set out (Scottish Government, 2009a).

Work is currently underway at the James Hutton Institute to analyse data to quantify the change in soil carbon when land is converted to forestry. Initial analysis indicates that converting moorland and semi-natural grassland to forestry leads to an increase in soil carbon (Chapman & Lilly, pers. comm). However, when looking at the carbon content of only the organic horizon it has been shown that birch trees (*Betula sp.)* grown on heather moorland have led to a reduction in the carbon content of the organic horizon (Mitchell *et al.,* 2007). This may have been due to disturbance of the soil by the planting, resulting in increased microbial respiration from aeration and loss of soil carbon as CO_2 to the atmosphere, and which might be expected to increase again as the trees establish. Further work is required to understand this better.

Furthermore, the selected location of new woodland will greatly influence the climate change mitigation and adaptation potential. The establishment of forestry on deep peat, as has occurred in the past, is now considered bad practice due to the potential to increase carbon loss by lowering the water table and increasing oxidation of the large carbon store in the peat. In addition, soil drying and shading resulting from the planted trees contributes to a loss of blanket bog (a priority habitat) by making the conditions unsuitable for bog plants (Lachance *et al.,* 2005), and in turn leads to a loss of waders which are reliant on the bog habitat (Stroud et al., 1988). Likewise, extensive planting or allowing natural regeneration, on other habitats of conservation interest i.e. dry shrub heath, could have negative effects on biodiversity. Alternatively, planting trees on low carbon soils would offer the best mitigation potential (Towers *et al.,* 2006).

However, careful positioning of trees in the landscape can also provide improved water management which may be an adaptation to higher rainfall. Narrow strips of trees planted across improved grassland (in Wales) have led to infiltration rates 60 times higher than areas of improved grassland without trees (Carroll *et al.,* 2004). They also have the potential to assist in the stabilisation of soils on steep slopes which are susceptible to high levels of run-off (SEPA, 2009). This could be particularly important with a trend towards wetter winters. These strips of trees also have the mutual function of providing shelter to livestock.

Careful positioning of areas of new tree planting can assist in the formation of habitat networks which will help species adapt to environmental change by moving through the landscape (Forestry Commission Scotland, 2009). This will be particularly important for species which are sensitive to climate change and require a network of appropriate habitats to enable them to expand into areas with a suitable climate (Hill *et al.,* 2001). On the other hand, tree planting can also act as a barrier to the dispersal of non-woodland species by fragmenting non-woodland habitats or act to facilitate the spread of undesirable pest species (Hampson & Peterken 1998). Furthermore, Hodgson *et al.* (2009) acknowledge that resources may be better spent by increasing the areas of existing woodlands or habitat quality.

Socio-economic constraints may also influence where woodland is planted. Historically commercial plantations have been sited mainly in upland areas unsuitable for food production. Establishing them in lowland farmland will reduce the area for crop production and livestock grazing, an option which has been met with opposition from the farming community (Towers *et al.,* 2006). Further woodland expansion in upland areas could impact on landscape aesthetics and recreational interests in the open countryside such as deer stalking, grouse shooting and hill walking, with both deer stalking and grouse shooting contributing substantial amounts to the Scottish rural economy (GWCT, 2010; Putman, 2013).

As well as the location of new woodland planting, the species grown is also an important consideration for climate change adaptation and mitigation. As discussed above, broadleaved trees sequester more carbon (Milne & Brown, 1997) and where native broadleaves are planted they can provide additional biodiversity benefits over non-native conifers. However, conifer plantations also contribute to carbon sequestration and the timber and wood products produced from them continue to store carbon into the future. Wood used in long lasting products such as construction timber, fencing panels and products made from Medium Density Fiberboard (MDF) store carbon for longer periods of time (40 + years), whilst pulp wood used for paper stores the carbon for a much shorter period (> 10 years) before decomposition occurs (Thompson and Matthews 1989). Furthermore wood products can be used as a substitute for more energy intensive materials such as concrete (Towers *et al.,* 2006).

Therefore woodland expansions can help to mitigate climate change by: (1) increasing carbon sequestration (so long as the new woodland is not sited on peat); (2) keeping carbon locked up in wood products and (3) providing timber which can be used in place of energy intensive materials in construction and (4) where woodland displaces livestock a reduction in methane emissions may be achieved. Woodland expansion can also help us to adapt to a changing climate by: (1) providing woodland networks (when trees are carefully sited) which allows species to extend their range northward as the climate becomes more suitable; (2) stabilizing slopes and reducing water flow allowing us to adapt to an increase in predicted storm events; (3) woodland expansion can, in some cases, enhance biodiversity.

However, converting an existing land use to woodland can result in conflicts: (1) woodland expansion on peat can lead to an increase in GHG emissions; (2) competition can arise when land required for crops and livestock is put into forestry; (3) trees can change the hydrology of an area by taking up water; (4) open upland habitats suitable for deer stalking and grouse shoot could be compromised leading to economic losses from these activities, and (5) some may consider woodlands to have a negative impact on the landscape.

Cropland expansion

Food security is a priority due to a growing population which demands more food and global climate change which has led to more extreme weather events negatively affecting food production in many parts of the world (Gregory *et al.,* 2005; Smith *et al.,* 2013). In Scotland it has been shown that changes in climate between the periods 1961 -1980 and 1981-2000 have led to areas of land (mainly in the east of Scotland) which were previously less suitable for arable production achieving climatic conditions which allows them to be classified as prime agricultural land (land which is suitable for growing a range of arable crops) (Brown *et al.,* 2008). Future predictions indicate a continuation of this trend with more land in the east becoming of prime quality (in this model topography, soil depth, stoniness and drainage are included together with climatic conditions), whilst only small changes will occur in the wetter west where the soil types and topography will still constrain agricultural production (Brown *et al.,* 2008). However, it is also recognised that as predicted conditions become drier in the east, drought may lead to the need for irrigation of crops (Brown *et al.,* 2011).

As the high demand for food creates an economic incentive to optimise production it is likely that this land will become under increasing pressure to be converted from its existing land use to cropland. Much of the marginal land predicted to become more suitable for arable production may currently be under woodland or rough grassland which may store large amounts of carbon and these habitats are also likely to be of high biodiversity value (Brown *et al.,* 2008). The loss of woodland to future prime agricultural land could lead to fragmented woodland habitats hindering species dispersal (Gimona *et al.,* 2012). Therefore, any changes in current land use to cropland could have negative effects on carbon storage and the maintenance of biodiversity.

On the other hand, it has been predicted at the UK level that there may be a future reducti on in arable land due to improvements in technology which will allow more food to be produced per unit area (Rounsevell & Reay, 2009). Depending on which of these two scenarios is realised will have a marked effect on the interactions between food production, climate mitigation and biodiversity conservation.

Therefore, cropland expansion is not likely to contribute to mitigation of climate change, in fact it is likely to increase GHG emissions through soil disturbance leading to carbon loss, but where climatic conditions become more suitable for crop production, opportunities exist for us to adapt our existing cropping area to include this new area of prime agricultural land. However, conflicts may arise from this land use change, as existing habitat will be altered and woodland habitats are likely to become further fragmented hindering the dispersal of woodland species.

Arable to grassland

Scottish cultivated top soils have been estimated to hold carbon equating to 18 years of greenhouse gas emissions from Scotland (Lilly & Baggaley, 2013). There could be carbon storage gains from careful management or converting cultivated land to permanent pasture. It has been calculated that these top soils have the potential to store a further 116 ± 14 Mt C (Lilly & Baggaley, 2013). However, grassland will normally be used for grazing, and the GHG emissions of the livestock involved need to be taken into account, particularly methane (emissions from enteric fermentation are accounted for under the agricultural sector for the purposes of the UK GHG inventory). Calculations based on normal stocking rates of beef, sheep and dairy and using IPCC default per head emission factors show that beef and sheep on grassland have a marginal positive abatement potential, whereas dairy cattle have a huge negative abatement potential (Figure 4).

Therefore, converting arable land to grassland can help to mitigate climate change by increasing carbon sequestration. However, adapting livestock farming to take advantage of the increased area of grassland for animal grazing/production could, in some cases, lead to increased GHG emissions negating the mitigation effect of the land use change. As with buffer strips (below), conversion of cropland to grassland may also result in better water management due to increasing infiltration rate and reducing runoff, helping adaptation to the wetter climates of the future.

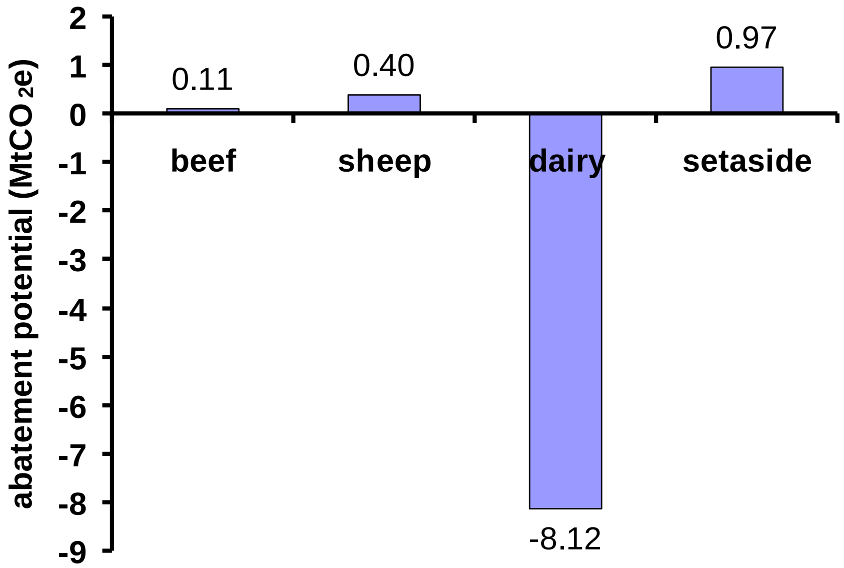

Figure 4: Abatement potential (Mt CO_2e) of beef, sheep, dairy and set-aside if all cropland in Scotland was converted to grassland-based systems. Soil C sequestration rate was assumed to be 1.5 t CO_2 ha^{-1} y^{-1}. IPCC per head emission factors used for GHG emissions from livestock.

Buffer strips

Semi-natural grasslands and woodland store more carbon than improved grasslands and arable land and there are benefits of allowing this habitat to form at field boundaries and in riparian areas. These areas are often referred to as buffer strips. As undisturbed areas of vegetation they act as a carbon store (Bowler *et al.,* 2012) but have further benefits such as intercepting the water running off of arable fields and pasture. This slows the water entering the streams, thus reducing flooding as well as capturing sediment and pollutants before they enter the watercourses (Schoumans *et al.,* 2014).

Furthermore, changes in climate are likely to lead to increases in stream water temperature which could impact on the functioning of aquatic systems. Wooded riparian buffers can provide shade, helping to mitigate this temperature change (Bowler *et al.,* 2012). They also add heterogeneity to the agricultural landscape and can provide habitat for invertebrate species some of which are predators of agricultural pests (Anderson *et al.,* 2013). A study has shown invertebrate species diversity to be higher in buffers ≥5.4m wide (McCracken *et al.,* 2012) whilst another found higher ground beetle activity density (a measure of local density and activity of beetles) and higher species richness at un-buffered sites compared to those with buffers. However, in this case, the beetle assemblages differed between buffered and un-buffered sites with buffered sites supporting beetle assemblages which more closely resembled those of woodland reference sites, indicating that they provide habitat for a certain suite of invertebrates (Stockan *et al.,* 2014).

Therefore, establishing buffer strips can help to mitigate climate change by increasing carbon sequestration, but it may also contribute to adaptation to future climates by, for example, (1) providing refuge areas for predators of agricultural pests; (2) providing habitats for pollinators; (3) reducing water flow and therefore assisting in flood management; (4) providing shade for watercourses, particular if shrubs or trees are included in the buffer, which prevents the water from warming and impacting on aquatic species and processes, and (5) creating diversity of habitats within the arable landscape and aiding species dispersal. However, conflicts could also arise when this land use displaces land used for food production and animals are prevented from accessing streams for water.

Peatland restoration

The vision for Scotland's National Peatland Plan is not to see any further losses of peatland by 2020 but instead to see improvements to degraded peatland due to restoration. Historically (in the 1970's and 80's) large expanses of peatland were afforested with non-native conifers. The bogs were drained to make the conditions more suitable for tree establishment at the detriment to bog species. There is now a drive to restore these areas to the original bog habitat. However, there has been much debate on whether this land use transition will have positive or negative effects on GHG emissions.

Yamulki *et al.,* (2013) found restored bogs produced more greenhouse gas emissions than afforested bogs, although their method was later found to be flawed (Artz *et al.,* 2013). However, a review by Morison (2012) concludes that there is no study in the UK which takes account of all the GHG fluxes in which to come to a conclusive answer. Whether a restored bog becomes a net GHG gas source or sink is dependent on the level of disturbance at the time of afforestation, various environmental conditions and the method of restoration together with the length of time since restoration (further work is required to understand the time period over which restored bogs to start accumulate peat again (Morison, 2012)). Removing trees and blocking drains will reduce the loss of dissolved and particulate organic carbon in water, as well as increasing the water table leading to less CO_2 emissions but it will also lead to greater emissions of CH_4 which is a more harmful greenhouse gas than CO_2. However, carbon will be sequestered when peat formation starts to take place but this will be offset by the loss of carbon stored in the felled trees, although converting them into long lasting timber products will help to retain this store. Furthermore, there may be an initial release of CO_2 and N_2O following decomposition of the brash and tree stumps. It is also recognised that it is only likely to be beneficial to remove trees and restore a bog at the time the trees are going to be harvested, rather than when they are younger and in a more productive state (Chapman *et al.* 2013).

Peatlands in their natural state and those which have been restored hold large amounts of water and can assist with flood mitigation by buffering the water entering rivers therefore reducing the risk of floods downstream (Wilson *et al.* 2011). They also act as a filter producing clean water (Ramchunder *et al.* 2012). Ramchunder *et al.* (2012) found drain blocking to result in improved water quality, subsequently leading to changes in in stream benthic macro-invertebrate assemblages. Furthermore restored bogs provide a vital habitat for internationally important breeding bird populations. Wilson *et al.* (2014) have shown that forest plantations create an edge effect reducing the number of Dunlin and Golden Plover breeding near to the forest edge, with the strongest effect occurring within 700m of the forest. Therefore restoring afforested bog is likely to benefit wader populations in the surrounding bog habitat as well as the area were trees are being removed.

Furthermore, restored peatlands support many specialised bog plants. Drain blocking re-wets the site and increases the cover of plant species typical of wet soil conditions, however, this response has been found to be variable and there appears to be a lag of several years after drain blocking before the effects of re-wetting lead to the establishment of peat forming plant communities (Bellamy *et al.* 2012). Restoring afforested peatland is also likely to reduce the chances of tick borne disease transmission. Gilbert (2013) found restored peatlands harboured less ticks compared to afforested bog.

Therefore restoring afforested peatland may help to mitigate climate change by increasing carbon sequestration, yet in some cases methane emissions may offset this effect and where timber is used in for long lasting products the carbon will remain 'locked-up', also helping to mitigate climate change.

Peatland restoration offers many opportunities for us to adapt to the effects of climate change: (1) restored bogs store water and release it more slowly which is particularly important with the prospect of increased frequency of storm events, (2) restoring the peatland habitat provides suitable habitat for upland waders, thus helping us to conserve biodiversity and (3) tick abundance is reduced on restored peatlands leading to a lower chance of tick borne disease transmission.

Renewable energy

Wind farms

Many wind farms are sited on upland peatlands. In their construction, peat is excavated to create the foundations and further peat disturbance arises with the construction of access tracks. There are also some cases where trees have had to be removed for access or to increase the wind reaching the turbines. All these factors contribute to carbon loss and may outweigh the carbon savings from wind energy. In fact, 30% of the total lifecycle greenhouse gas emissions of wind farms are associated with their construction (Amponsah *et al.,* 2014). Smith *et al.* (2014) conclude that wind farms on un-degraded peats are unlikely to further reduce carbon emissions. On the other hand, if wind farms are sited on mineral soils they can lead to net carbon savings.

Bioenergy crops

It is Scottish Government policy to generate the equivalent of 100% of Scotland's gross annual electricity consumption from renewable sources by 2020, and it plans to decarbonise the energy (heat and electricity) sector with 100% renewables by 2050. To help meet these targets, the production of biomass or bioenergy crops has been proposed as a way of reducing or offsetting emissions of CO_2 from fossil fuels. In the UK, biomass crops such as short-rotation coppice willow (SRC), poplar, *Miscanthus* (elephant grass), switch grass, and reed canary grass are perennials that have been identified for potential use. Although the above-ground harvested bio-fuel is likely to be the major contributor to the CO_2 mitigation potential of bioenergy crops, additional carbon may be sequestered through crop inputs into plantation soils. However the processes influencing soil organic carbon (SOC) stocks following land use change to bioenergy crops are not well understood.

In an early modelling study, Grogan & Matthews (2002) found that the potential for soil carbon sequestration in these willow plantations was comparable to, or even greater than, that of naturally regenerating woodland, and that the sequestration potential was greatest in soils whose carbon content had been depleted to relatively low levels due to agricultural land use practices such as annual deep ploughing of agricultural soils. In a subsequent review of existing literature, Cowie *et al.* (2006) similarly concluded that losses of soil C were most likely where stocks are initially high, such as where improved pasture is converted to biomass crops, and that gains in SOC are more likely to occur where conversion is from land used for conventional cropping where stocks have been depleted by repeated cultivation. Similar results were reported by (Hillier et al. (2009b) who found that previous land use was important, and could make the difference between the bioenergy crop having a positive or a negative net abatement potential. In a global review, Anderson-Teixeira et al., (2009) noted that converting uncultivated land to bioenergy crops will result in SOC loss that counteracted the benefits of fossil fuel displacement. This contrasts with the conclusion of Cowie *et al.* (2006), who argued that loss of SOC is negligible compared to the contribution of bioenergy systems towards GHG mitigation through avoided fossil fuel emissions.

Cowie *et al.* (2006) noted that SOC could be enhanced by maintaining bioenergy crop productivity through application of fertilisers, inclusion of legumes, and retention of nutrient-rich foliage on site. Shibu *et al.* (2012) explored some of these management options in more detail in the Scottish context with a simulation model, and found that increasing plant density and decreasing harvest frequency increased the GHG abatement potential. They also found that applying N-fertilizers at a rate of 50-100 kg N ha^{-1} resulted in the build-up of SOC, but only if the amount of SOC was less than 180 Mg C ha^{-1} – in soils with greater SOC contents, annual emissions resulting from N fertilizer application were greater than the carbon saving through marginal increases in wood yield and SOC changes. This is consistent with the findings of others that the initial SOC content is highly important in determining whether conversion to bioenergy crops will have a positive or negative effect on soil carbon. The study was also consistent with the conclusion of Cowie *et al.* (2006) that benefits from fossil fuel substitution far outweighed any losses in soil carbon, with overall abatement potentials ranging from 8.8 – 13.2 $tCO_2e\ ha^{-1}\ yr^{-1}$ depending on species and crop management (Shibu *et al.,* 2012).

Thus, the consensus so far for conversion of land to growing bioenergy crops seems to be that it is beneficial in terms of net impact on reducing net GHG emissions due to fossil fuel substitution, but that its impact on soil carbon depends on what the previous land use, and hence initial soil carbon level, was. However, it must also be remembered that conversion of forest to growing bioenergy crops will mean a net loss in above ground carbon with the replacement of mature trees with young growing trees (depending on the end use of the mature timber), and conversion of arable cropland to bioenergy crops may mean that those food crops are displaced elsewhere (either within Scotland, or abroad), both reducing any net benefit that fossil fuel substitution will have. Impacts on biodiversity and hydrology will also depend on the previous land use and bioenergy crop management.

6. Conclusions

In this review we have summarised the baseline carbon stores for each land use type, noting that there is a wide range of carbon stock values given for different land uses. This is, in part, due to the variation in soil properties within a land use type and in many cases within a land holding as well as the wide range of land management options adopted within the same land use category.

We have also provided an indication, based on the available data, of how land use change may contribute to climate change adaptation and mitigation (summarised in Table 3). Some land use changes may only offer either adaptation or mitigation potential whereas others may provide co-benefits. For example, restoration of peatland acts to mitigate climate change by contributing to carbon sequestration and preventing the loss of dissolved and particulate organic carbon in water, but also has the additional downstream benefit of regulating the flow of water into rivers and thus reducing the chance of flooding from increased rainfall/storm events. Duguma *et al.,* (2014) recognise the benefits of situations such as these where there is synergy between mitigation and adaptation and a 'win win' situation is achieved. A less satisfactory situation is encountered when mitigation measures such as tree planting impinge on other land use objectives such as food production leading to conflicts of interest.

Of the potential land use changes likely in Scotland, woodland expansion generally leads to greater carbon sequestration, both in the soil and the biomass, and can therefore help to mitigate climate change by reducing net GHG emissions, but this will depend on where the new trees are located. There are also biodiversity implications in relation to the possible destruction of habitats and the creation of new ones. The amount of land in Scotland suitable for arable agriculture is predicted to increase under future climates, but thought needs to be given to whether woodlands should be planted now where crops might be grown in the future. Intensification of crop production on existing areas may reduce the pressure on existing woodlands in this way, but may also result in increased GHG emissions if this intensification is achieved by increased fertiliser use. Conversion of existing arable land into grassland is likely to increase soil carbon stocks, but the overall net benefit in terms of global warming depends on the use to which grassland is put. Buffer strips of semi-natural grassland and/or trees in riparian areas alongside cropland have the potential to increase the sequestration of carbon in the landscape, improve biodiversity, and prevent runoff of agricultural pollutants into watercourses.

Restoration of degraded peatland has the capacity to store large amounts of carbon from the atmosphere and contribute significantly to meeting GHG emission reduction targets, but again this depends on the nature of the existing degradation, with it being unclear as to whether restoration of pealands under forestry is beneficial. Restoring peatlands by rewetting may also result in an initial production of methane, which will offset any potential carbon gains from restoration, again delaying the time to achieve net carbon benefits. There are likely to be biodiversity and water management benefits, however. Despite windfarms producing renewable energy that can be used to substitute for fossil fuels, siting on deep peats can result in significant CO_2 losses resulting from soil disturbance and biodiversity loss due to habitat destruction. Siting on degraded peatland areas and areas with mineral soils is less likely to be as significant in this regard. The effects of conversion of land to bioenergy crops also largely depend on the previous land use. For example, conversion of forestland to bioenergy crops will result in a loss of both above (in the vegetation) and below-ground (in the soil) carbon, whereas conversion of cropland will result in higher above ground carbon and gradual accumulation of soil carbon. However, the latter land use change may also result in displacement of crop production and its associated GHG emissions elsewhere, either in Scotland or abroad, offsetting any net abatement potential. Impacts on biodiversity and hydrology will also depend on the land-use prior to conversion to bioenergy crops.

It is important, therefore, that these climate mitigation and adaptation issues be taken into consideration when addressing future land use. We have also identified a number of areas where further research is required – specifically, more information is required (in a Scottish/UK context) relating to the rate of carbon loss and carbon gains when land use transitions occur, and in the trade-offs and synergies between mitigation and adaptation. This will enable better informed decisions to be made, particularly where a short term increase in GHG emission may lead to longer term benefits.

Table 3. Different land use change options and their implications for mitigation and adaptation. C=Cropland, F=Forestland, W=Wetland, G=Grassland, G-rough= rough grassland, S=Settlement, Other = Other

Intervention	Sub category	Land use change	Mitigation effect	Adaptation effect	Ecosystem service	Conflicts
Woodland expansion	• Plantation - generally non-native spp. • Native woodland • Woodland buffer strips	• C - F • G – F • W - F	• Increased carbon sequestration (if not on peat) • Reduced GHG emissions by using more wood products as an alternative to energy intensive materials • Might displace livestock & therefore decrease CH4 emissions	• Enhancing biodiversity (depending on nature of the stand + habitat it has displaced) • Creating habitat networks to aid spp dispersal • Shading watercourses • Slope stabilisation • Reducing water flow/flood management	***Regulating –*** Carbon sequestration, shading watercourses, slope stabilisation, reducing water flow, ***Supporting –*** Habitat for woodland spp ***Provisioning –*** raw materials for building ***Cultural –*** place for recreation	• Woodland expansion on peat leads to increase GHG emissions • Competing with land required for crops and livestock • Could affect regional water balance • Negative effect on landscape??? • Impact on game - loss of grouse and deer habitat leading to economic losses
Cropland expansions		• W-C • G-C		• Using areas which are suitable for crop production due to climate change	***Provisioning -*** Food production	• Displaces woodland – implication for habitat networks Soil disturbance and carbon loss

Intervention	Sub category	Land use change	Mitigation effect	Adaptation effect	Ecosystem service	Conflicts
Arable to grassland		• C-G	• Increased soil carbon sequestration	• Increase grazing area for livestock • Better water management in some areas.	***Regulating* –** Carbon sequestration ***Supporting* –** Enhanced biodiversity is converted to semi-natural grassland ***Provisioning* -** Food production if area is used for livestock grazing	• Increased GHG emissions if the area is used for livestock production
Buffer strips	Rough grazing	• C-G	• Increased soil (and possibly vegetation) carbon sequestration	• Control of agricultural pests and diseases • Habitat for pollinators • Reducing water flow/flood management • Creating habitat networks to aid spp dispersal • Shading watercourses	***Regulating* –** Control of agricultural pests and diseases, pollination, improving water quality ***Supporting* –** habitat for invertebrates	• Loss of land for food production • Animals cannot access streams for water

Intervention	**Sub category**	**Land use change**	**Mitigation effect**	**Adaptation effect**	**Ecosystem service**	**Conflicts**
Peatland restoration		• F-G	• Increased soil carbon storage	• Broader benefits of water management within catchment in face of increased storm events??? • Reduced tick abundance & thus less chance of tick borne disease transmission • Habitat for breeding waders • Habitat for plants i.e sundews	***Regulating* –** Carbon sequestration, Disease control, water storage/regulation of down-stream flow ***Supporting*** - habitat for breeding waders, ***Cultural* –** Bird watching, nice landscape ???, deer stalking, grouse shooting ***Provisioning*** - clean water, clean water entering streams - good for Salmon?, area for sheep grazing/production, venison	• Could increase methane emissions

Review of implications of land use change on climate change mitigation and adaptation

Intervention	Sub category	Land use change	Mitigation effect	Adaptation effect	Ecosystem service	Conflicts
Renewable energy	• Wind farms • Biofuel • Biomass	• W-Other • G-Other • C-Other • W-C • G-C • G-W • C-W	• Reduction of GHG emissions through use of wind energy • Net reduction of GHG emissions from producing energy from short rotation coppice and biofuel rather than from fossil fuels. • Bioenergy crops may affect soil carbon levels positively or negatively depending on previous land use.	• Farm diversification – alternative income streams • Bioenergy crops may be grown in areas now marginal due to climate, but which may be suitable in the future. However, this may have soil carbon implications.		• Often in areas where trees could be grown • Not aesthetically pleasing??? • Bird collisions • Disturbance of peatland – CO2 loss • Increased fertiliser use – leading to GHG emissions ??? • Biomass/biofuel – loss of land for food production • Negative effects on biodiversity

Intervention	Sub category	Land use change	Mitigation effect	Adaptation effect	Ecosystem service	Conflicts
Settlements		• G-S • W-S • C-S				• Soil removal leading to increased CO_2emissions • Loss of habitat/biodiversit y • If settlement is established in a remote area an increase in travel and associated GHG emissions

7. Appendix

Appendix I. Dawson, and. Smith. (2007).

Potential changes in soil C storage in terms of conversion of land-uses

Land-use change	Net C rate[a] and *uncertainty* ($\times 10^3$ kg C ha^{-1} yr^{-1})	Reference
Arable to ley:arable rotation	1.6	Smith et al. (1997)
Arable to grassland (50 yr)	0.3–0.8	IPCC (2000)
Arable to grassland (35 yr)	0.63	Jenkinson et al. (1987)
Arable to grassland (15–25 yr)	0.3–1.9±0.6, *110%*	(Vleeshouwers and Verhagen, 2002; Guo and Gifford, 2002; Murty et al., 2002)
Arable to grassland short leys (20 yr)	0.35	Soussana et al. (2004)
Arable to permanent pasture	0.27	Post and Kwon (2000)
Arable to forestry (115 yr)	0.52+1.53(C in veg.)	Hooker and Compton (2003)
Arable to forestry	0.62+2.8(C in veg.)	(Smith et al., 2000; Falloon et al., 2004)
Arable to forestry (25 yr)	0.3–0.6, *>50%*	(Guo and Gifford, 2002; Murty et al., 2002)
Arable to forestry	0.5–1.4, *>50%*	Maljanen et al. (2001)
Permanent crops to arable	−0.6 and 1.0–1.7, *>50%*	(Smith et al., 1996; Guo and Gifford, 2002; Murty et al., 2002)
Grassland — arable (20 yr)	−0.95±0.3, *95% CI*	Soussana et al. (2004)
Grassland — arable	−1.0 to −1.7, *>50%*	(Smith et al., 1996; Guo and Gifford, 2002; Murty et al., 2002)
Grassland — afforestation (general, 90 yr)	0.1±0.02, *95% CI*	Soussana et al. (2004)
Moorland — grassland	−0.9 to −1.1	Soussana et al. (2004)
Forestry — arable	−0.6	(Guo and Gifford, 2002; Murty et al., 2002)
Forestry — grassland	−0.1±0.1, *95% CI*	Soussana et al. (2004)
Native vegetation — grassland	0.35	Conant et al. (2001)
Peatland — cultivation	−2.2 to −5.4	Freibauer et al. (2004)
Wetland — arable (temperate and boreal)	−1.0 to −19	Watson et al. (2000)
Wetland restoration	0.1–1.0	Watson et al. (2000)
Revegetation on abandoned arable	0.3–0.6, *>50%*	Poulton (1996b)
Revegetation on wetlands from arable	2.2–4.6, *>50%*	Kamp et al. (2001)
Revegetation on wetlands from grassland	0.8–3.9,*>50%*	Kamp et al. (2001)
Conservation	>2.2, *>50%*	Freibauer et al. (2004)

[a]+ve value indicates soil C-gains, −ve value indicates soil C-losses.

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