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Soil Carbon and Land Use in Scotland

Final Report

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Executive Summary

Soil carbon has been identified as a priority issue by the Scottish Government in climate change policy across several areas. There is particular interest in the potential of soils to provide carbon sequestration as a contribution to the annual emissions reductions targets, with links to agriculture, renewable energy and other primary land uses.

This project synthesises the current state of knowledge on soil carbon and land use in Scotland.

1. Key findings

- There is strong scientific evidence of consensus in several key areas including the importance of Scottish soils for the storage of carbon, and the amounts of carbon stored in different soil types across the country
- There was an absence of evidence around potentially key issues including the amount of carbon that can be sequestered by restoration of organic soils, rotational grass, the future carbon sequestration potentials of long term grasslands and arable soils
- The evidence base is consistent on the overall levels of soil carbon in Scotland (around 3000 Mt), and on the amount (1600 Mt) stored in peats and peaty soils.
- The available evidence suggests that there have been no significant changes in the storage of carbon taking place in arable or grassland soils since 1978. However, it can be demonstrated that older grasslands (greater than 5 years) will store more carbon
- The uptake of atmospheric carbon dioxide (CO_2) by land use and land use change (10 Mt CO_{2e}/year) is of a similar magnitude to the total greenhouse gas emissions from agriculture in Scotland
- There is broad agreement across the evidence studied that some opportunities exist to use agricultural management to increase carbon storage in agricultural soils (estimated to be 174 Mt C), although there are possibly greater opportunities to reduce non CO_2 greenhouse gas emissions from agriculture (currently 7.4 Mt CO_{2e}/year)
- Emissions of gases other than CO_2 (methane and nitrous oxide) dominate agriculture's contribution to greenhouse gas emissions. An improved understanding to these emissions is likely to lead to greater opportunities for mitigation than that provided by increasing carbon sequestration
- The evidence base is consistent in the conclusion that peatland restoration offers significant opportunities to increase carbon storage in Scottish soils but there are large uncertainties (ranging between a net uptake of 8.1 Mt CO_{2e}/year to net loss of 2.8 Mt CO_{2e}/year)
- There are considerable uncertainties in predicting the future effects of land use change, climate, and management and their interactions on future carbon stocks. This is due to uncertainties in future global atmospheric greenhouse gas concentrations, and the consequent response of soils to altered climatic conditions
- The UK and Scottish inventories of greenhouse gas emissions and removals do not currently report changes in soil carbon stocks in areas of grassland and cropland that remain in the same

land use. As new evidence emerges of such changes it is likely in future that new reporting procedures will be adopted that reflect such changes

- Work is ongoing in trying to establish better emission factors for the UK peatlands. It is expected that the findings of a DECC-funded project, which will collate both the historic and the most recent UK-relevant data, will be published in the near future.

2. Introduction

Scotland's soils are characterised by their high soil carbon content. Soil carbon is mostly contained in soil organic matter and is derived from biological activity. Some soils also contain inorganic carbon in the form of carbonate (derived from rocks) and coal, however the soil carbon referred to in this report describes carbon contained in organic matter pools derived from biological activity. Soil carbon is an essential attribute of good soil quality, contributing to soil fertility and a wider range of soil functions. But the carbon locked up in soils also has an important role to play in combating climate change, because carbon dioxide (CO_2) can be removed from the atmosphere (by plants) and added to soil thereby reducing the warming effect that excess carbon dioxide exerts on our climate. The future management of our soils is critically important in determining the fate of this carbon. Projected climate change threatens to promote conditions in which loss of soil carbon becomes more likely. However, management interventions in peatlands, forests and agricultural soils can be used to slow or even reverse such changes. Such measures would be important both in terms of climate change mitigation and adaptation. Maintaining or enhancing soil carbon stocks is also recognised as critically important to maintaining soil quality and delivering a wide range of ecosystem services.

This project was commissioned in October 2015 with the objective of synthesising the current state of knowledge on soil carbon and land use in Scotland. The project used a rapid evidence assessment (a 'stock-take') approach involving an expert group covering soil science, forestry and agriculture. The group were asked to provide an assessment of:

a. Soil types in Scotland, and their relative carbon content (with peatland soils featuring strongly)

b. Greenhouse gas emissions from the range of dominant land uses and related management practices in Scotland

c. The soil carbon abatement potential across the range of dominant land uses in Scotland

d. The impacts of land use change and potential impact of future change on soil carbon

e. The relative carbon impact of specific different land management practices on-the-ground

In compiling the report, the group were also asked to highlight areas of uncertainty, where the current scientific knowledge is incomplete or ambiguous. This report will provide support for the Scottish Government's development of the Third Report on Policies and Procedures (2017-2032) due to be published early in 2018.

3. Methodology

The project team were invited to undertake a Rapid Evidence Assessment of soil carbon storage and sequestration in Scottish soils. A Rapid Evidence Assessment identifies evidence available on a particular topic and provides a critical assessment of this evidence. It is recognised that the Rapid Evidence Assessment is less rigorous and comprehensive than a systematic review, but has greater rigour and analytical power than a simple literature review (Collins, 2014).

An initial attempt to undertake a review of the available literature on the topic of soil carbon revealed that a large body of evidence was available in the form of published papers that was related to this topic (over 20,000 hits over the past 10 years for searches on "soil and carbon"). It was considered that filtering out relevant publications would be very time-consuming. Furthermore, individual members of the group have recently been involved in expert reviews of the literature which could usefully inform the questions being asked by the steering committee. Following discussions between team members, individuals within the group were subsequently tasked with drafting responses to the individual questions asked, and the group as a whole then invited to comment on and revise the draft report. This review can therefore be considered to represent a hybrid of an Expert Report and a Rapid Evidence Assessment.

4. Soil types in Scotland, and their relative carbon content

What we know

There is a well-established record of soils research in Scotland and a good understanding of the soil resources that are present within its landscapes. A rigorous inventory of our soil resources has been undertaken by the James Hutton Institute and its predecessor, the Macaulay Land Use Research Institute. This research tells us that Scottish soils contain large quantities of carbon, with a total stock of just over 3000 Mt C. (Table 1 and 2). Peaty soils contain 72% of this carbon with the remainder being divided between the mineral soil groups.

There are a number of independent sources of information from which the carbon content of Scottish soils can be determined adding to the robustness of the evidence base. These include the Scottish Soils Database and its derivative, the Scottish Soils Knowledge and Information Base (SSKIB), the National Soil Inventory of Scotland (NSIS) which is a subset of the Scottish Soils Database (all held at the James Hutton Institute), the European-wide Land Use/cover Area framework Survey LUCAS dataset (Orgiazzi *et al*, 2017), Forest Research's BioSoil (https://www.forestry.gov.uk/fr/biosoil) and the CEH Countryside survey (http://www.countrysidesurvey.org.uk). These provide the raw material for much of the evidence base examined here. There are also national scale predictions using traditional soil (Lilly *et al*, 2014), mapping and the databases described above combined with geostatistical techniques (Poggio & Gimona, 2014) or artificial neural networks (Aitkenhead *et al,* 2016). Carbon stocks (concentration x density x depth) to 1 m are available for SSKIB, NSIS and Biosoil while Countryside survey has stocks only to 15 cm and LUCAS has only topsoil carbon concentrations.

For the purposes of this assessment, Scottish soils were grouped according to their similarity in behaviour and characteristics, separating mineral soils from those with a peaty surface layer (Table **1**). The most abundant of these by area was determined from the 1:250 000 scale national soil map of Scotland and occupy just under 90 % of Scotland's land area.

Table 1: Areal extent of the main soil types in Scotland.

Rank	Amalgamated soil type*	Component major soil subgroup	Areal extent (Ha)	Percentage area

1	Peat	Blanket peat, Basin peat, Semi-confined peat	1, 726320	22
2	Mineral gleys	Brown earths with gleying, Calcareous, Humic, Magnesian & Non-calcareous gleys	1,263040	16
3	Peaty gleys	Peaty gleys, Peaty alluvial soils	1,080990	14
4	Brown soils	Brown calcareous, Brown magnesian, Brown rendzinas and Brown earths	997970	13
5	Mineral podzols	Humus iron podzols	928430	12
6	Peaty podzols	Peaty and subalpine podzols	908360	12
	Total		**6, 905110**	**89**

The carbon stock for these amalgamated soil types is given to a depth of 1 m. These were then used to calculate total stocks) for each of the amalgamated soil types by multiplying this carbon stock of each soil series by its areal extent (Table 2). The remaining soil types were estimated to have around 196 Mt C to 1 m giving a national total of 3056 Mt with a range of between 2620 and 3492 Mt when uncertainties associated with predicting bulk density and the range of carbon concentrations for each soil type were considered.

Table 2. estimated carbon stocks to 1 m depth in the main soil types in Scotland (Mt).

	Carbon stock (Mt) to 1m depth		
	Mean stock	**Lower estimate**	**Upper estimate**
Peat	1232	1115	1349
Mineral gleys	285	236	335
Peaty gleys	443	347	539
Brown soils	276	228	324
Mineral podzols	250	206	293
Peaty podzols	374	313	435

*Mt = 1, 000000 metric tonnes

The total stock estimate was similar to that estimated using other methods (e.g. Poggio & Gimona 2014; Aitkenhead & Coull, 2016; and Bradley *et al*. 2005, providing considerable confidence in the estimate of total soil carbon stocks.

The National Soil Inventory of Scotland (NSIS 2007-9) was also used to estimate the carbon stocks on a per hectare basis by amalgamated soil types based on 179 sample points (Table 3). These data highlights the importance of peats and peaty soils in storing soil carbon in Scotland's landscapes.

Table 3. National Soil Inventory of Scotland (2007-2009) profile carbon stocks to 1 m depth by amalgamated major soil subgroup.

	Carbon stocks t/ha			
	Average	**Least**	**Greatest**	**Number profiles***
Peat	547	273	823	52
Mineral gleys	131	49	271	30
Peaty gleys	242	121	402	20
Brown soils	115	61	204	20
Mineral podzols	124	52	263	23
Peaty podzols	214	128	353	16

* Plus 18 other soils mainly oroarctic, alluvial and shallow soils.

Areas that are subject to active research and debate (i.e. where there is uncertainty or ambiguity)

The use of different databases to report soil carbon stocks potentially introduces discrepancies in the data reported. Reconciling, the Scottish Soils Knowledge and Information Base (SSKIB) and the National Soil Inventory of Scotland (NSIS) 2007-2009 is the main source of uncertainty. Different methodologies used to estimate soil bulk density and stone content (used to calculate soil carbon stocks) give rise to different estimates of total soil carbon. The NSIS soil profiles tended to have a lower overall carbon stock compared to the SSKIB equivalent which explains why data from Chapman *et al*. (2013) gives an estimated the total carbon stock of Scottish soils at 2080 Mt. These differences in methodology lead to variations in the total soil carbon stock of Scottish soils of 31%, although it is not possible to identify which methodology is closer to the true value.

What we don't know

Scotland's knowledge of it's soil resources is better than that available in many countries, however, significant knowledge gaps remain. These include uncertainties associated with fine scale spatial distribution of soil types (which is important at the field scale for managing soils and soil fertility), and the response of soil carbon stocks to climate change. This in turn will depend upon on interactions between soils, plants and the physical and chemical environment which are difficult to predict on the basis of current knowledge, but are the subject of ongoing research.

5. Soil carbon abatement potential across a range of dominant land uses in Scotland:

What we know

Scotland's cultivated topsoils are relatively rich in carbon (around 4% on average) but it is known that they have the potential to store additional carbon. Lilly, (2013) calculated the potential for Scottish cultivated mineral topsoils that are regularly managed to store additional soil organic carbon. This was achieved by calculating the difference between the stocks based on the calculated median carbon concentration and those based on the observed maximum carbon concentration for each soil series was determined following the method proposed by Stolbovoy and Montanarella (2008). This demonstrated that Scottish managed topsoils have the potential to store an additional 174 (150–215) Mt C. However, by repeating the calculation but using the difference between the median and the minimum stock, there is a potential for Scottish cultivated topsoils to lose 112 ± 12 Mt C. The overall amount currently stored was estimated to be 246 ± 9 Mt (Lilly, 2013).

Trends in soil carbon stocks

Changes in carbon concentration and stocks over time at a national scale have been measured by CEH Countryside Survey, National Soil Inventory of Scotland and the Scottish Agricultural College (SAC) analytical laboratory (Buckingham *et al*, 2013). Overall, all they found little change in carbon contents over a 20-30 year period. Reynolds *et al*, (2013) reported significant changes in mean carbon concentration in Scotland between 1978 (23.9%) and 1988 (25.8%) and between 1998 and 2007 (24.2%) but no significant change in concentration between 1978 (23.9%) and 2007 (24.2%) for 2614 samples. Taken together these studies indicate that while there may be small changes within individual land use categories over short time periods, over longer periods there is no strong evidence of significant carbon stock changes in Scottish soils.

Chapman *et al*, (2013) found, following resampling of the National Soils Inventory, that there were no significant change in carbon stocks from 0-15 cm for those soils under arable cropping for samples taken between 1978-88 and 2007-9 (179 soil profiles) nor did they find any significant change in carbon stocks to 1m depth for this land use. The only land use type that showed a significant increase in carbon stock to 1 m depth (after removing deep peats from the analysis) was (largely coniferous) woodland (163.2 ± 24.1 to 186.7 ± 26.9 t/ha).

The potential abatement from peatland restoration has been estimated to be between 0.6 and 8.3 t CO_2e /ha/year, depending on the initial peatland condition (Artz *et al.* 2012). A follow-up study estimated that existing peatland restoration would give current (2012) carbon savings of 0.018 Mt CO_2e/year, and that by 2027 national carbon savings of 1.5 – 5.4 Mt CO_2e /year could be made if all degraded peatlands were restored immediately (Chapman *et al.* 2012). Given the scale of work involved, immediate restoration was not practical and a third briefing estimated the carbon benefits attainable through a more realistic restoration program (Chapman *et al,* 2013) would give an annual abatement of 0.4 – 0.7 Mt CO_2e /year by 2027. There are relatively few studies of full carbon budgets in peatlands, but the findings of Chapman were consistent with carbon uptake measured at a peatland site just south of Edinburgh (Billet et *al*. 2010) where over a period of two years the site acted as a small net carbon sink with uptake of 0.4-1 t C/ha/ year.

Areas that are subject to active research and debate (i.e. where there is uncertainty or ambiguity?)

The actual losses from Scottish topsoils could be greater than those estimated by assuming the minimum observed carbon concentration is the actual minimum a soil will attain. Work by Hassink (1997) suggested that the amount of carbon that can be sequestered over the long term (as opposed to stored in the short term) in mineral soils was dependant on the proportion of clay and silt sized particles. Based on the same data used by Lilly and Baggaley (2013), this theoretical minimum carbon stock that is sequestered in cultivated mineral topsoils in Scotland was estimated to be 116 ± 14 Mt suggesting that the potential loss could be as great as 131 (109 - 153) Mt. However, there is uncertainty regarding the role of soil texture as opposed to other soil and environmental conditions remains uncertain and is the topic of ongoing research.

A CxC workshop in 2013 (www.climatexchange.org.uk) on the potential for grasslands to sequester carbon concluded that managed grasslands would not continue to accumulate carbon indefinitely, and the literature suggests that changes in grassland carbon are often attributable to legacy effects (Smith, 2014). This is consistent with evidence from a comparison of grassland sites sampled during the first NSIS (1978-88) and the revisited sites in 2007-9, showed a non-significant decline in carbon stock of 4.5 t/ha. A decline in concentration over the same period was offset by an increase in thickness of grassland topsoils (in other words a redistribution of existing carbon within the profile).

What we don't know

Uncertainties in the potential for Scottish soils to sequester additional carbon overlap with uncertainties in defining carbon stocks and how these will change (Section 2). Soil management and climate will be the major drivers of changes in future carbon stock, but uncertainties in these factors and how they interact are the largest single factor that limit our prediction of future carbon stocks. The role of these factors in influencing future carbon stock is an area of active research, however, the issues are complicated by underlying biological and physical controls of carbon turnover in soils and uncertainty of predictions of future climatic conditions.

6. Greenhouse gas emissions from the range of dominant land uses and related management practice in Scotland

What we know

Agriculture is the dominant land use in Scotland occupying around 70% of the land area. However, more than half of the agricultural area is classified as rough grazing with only 11% used for cropping or left in fallow. Agricultural land-use plays an important role in contributing to the country's national greenhouse gas emissions, with most of these emissions being focused in the more intensive agricultural areas associated with intensive livestock production and cropping.

The national greenhouse gas inventory provides an official estimate of greenhouse gas emissions in Scotland, and highlights the importance of land use in contributing to overall carbon emissions (Scottish Government, 2016). Agriculture and related land uses represent the third largest source of emissions at the national level, responsible for 10.7 Mt CO_2e /year. Nearly 75% of these emissions are associated with non-CO_2 emissions (described below), with the remaining CO_2 emissions mostly associated with land use change (described in other sections of this report). The forestry sector provides a net carbon sink of 10.2 MtCO_2e /year offsetting much of the emission sources derived from the agriculture sector (Figure **1**).

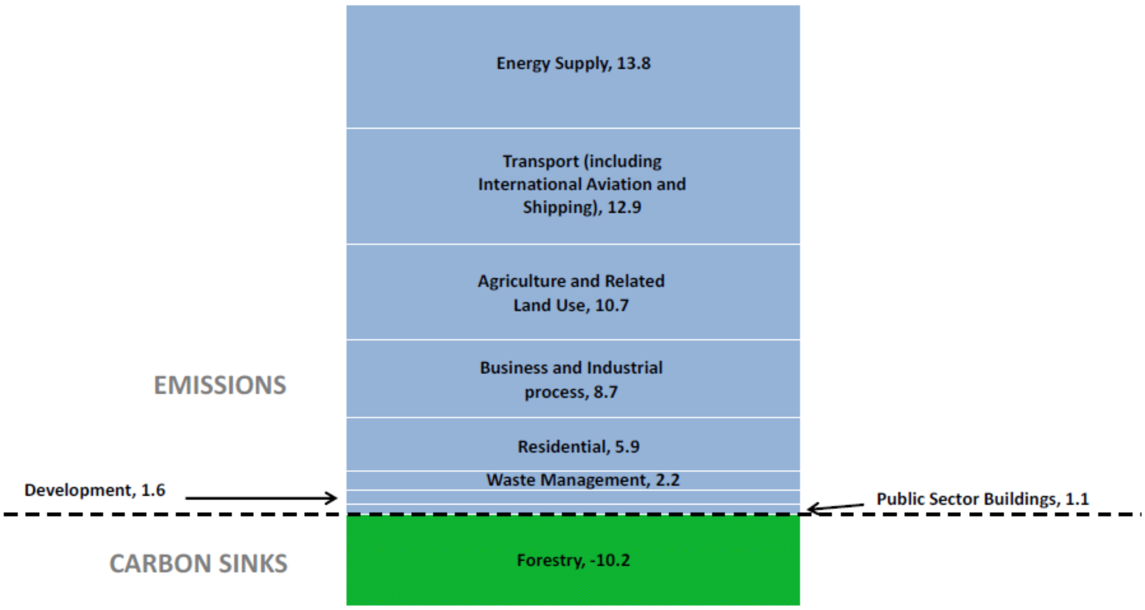

Figure 1. Sources and sinks of greenhouse gases (Mt CO_{2e}) in Scotland in 2014 (Scottish Government 2016).

Rotational land use in agriculture involving the cycles of grass and arable farming result in sequential uptake and release of carbon, however, a unique feature of the Scottish accounting systems allows these agricultural sources and sinks to be assigned to the agriculture compartment allowing a more accurate assessment of agriculture's net contribution of agricultural sources and sinks to be identified (Bell *et al,* 2014).

Greenhouse gas emissions from agriculture are largely associated with emissions of nitrous oxide (N_2O) and methane (CH_4). Nitrous oxide is a powerful greenhouse gas with a Global Warming Potential that is 298 times greater than that of CO_2, which is emitted from nitrogen based fertiliser and animal wastes added to soils. Scotland and the UK currently use an IPCC Tier 2 approach to reporting emissions. This is an approach that is based on nationally derived (UK) emission factors that represent average emissions for UK conditions (Ball *et al,* 2014; Bell *et al,* 2016; Hinton *et al,* 2015). The majority of countries currently report nitrous oxide emissions using a simpler Tier 1 approach which uses emission factors that describe average global conditions. The UK and Scotland's approach has identified deviations in observed emissions from those previously modelled in IPCC reports using Tier 1 methodologies. For example, emissions from arable crops would appear to be lower than those assumed in the inventory (Bell *et al,* 2015). In 2014 nitrous oxide emissions from Scottish agriculture were 2.7 Mt CO_2e.

Agricultural methane emissions are largely associated with ruminant livestock production, with emissions reported using a Tier 2 approach, which takes account of livestock type and management. In 2014 it is estimated that methane emissions from livestock production were 4.7 Mt CO_{2e}. Since 2009, agriculture has become the main source of methane emissions and now exceeds that from all other sources (mostly energy supply and waste management). It is recognised that improved agricultural management techniques provide many opportunities for reducing emissions of methane and nitrous oxide from the agricultural sector, and recent analysis has shown that such measures can often be cost effective (Moran *et al,* 2011).

Areas that are subject to active research and debate (i.e. where there is uncertainty or ambiguity?)

National inventory reports of greenhouse gas emissions are prepared using internationally agreed emission factors to estimate the relationship between activities and greenhouse gas emissions. Such emission factors provide approximate estimates of emissions often averaged over large regional areas of the globe. The UK has now implemented a Tier 2 reporting system using more regionally appropriate (UK based) emission factors. Further refinement of this approach will take place in coming years as the findings of new research emerge.

For the purposes of inventory reporting it is assumed that agricultural categories of land remaining under constant management (e.g. grassland remaining as grassland) neither gain or lose carbon. This is a contentious issue since research studies often report gains or losses of carbon as a consequence of management that does not involve land use change. However, justification for this approach is provided by an assumption that under constant conditions, soil carbon stocks will reach an equilibrium value and that many observed changes in carbon stocks result from historical land use change extending back over recent decades (Smith, 2014). This is an ongoing area of research and a combination of modelling and measurement from sites across the UK is currently being undertaken in a project being funded by the Department of Climate Change (2016-2017) to determine whether we can improve the reporting of changes in soil carbon stocks in grasslands. This study has demonstrated that grasslands older than 5 years store significantly more carbon than younger soils (the report will be published in 2018). Forestry is always expected to contribute to carbon sequestration although rates of carbon uptake vary according to the type and age of woodland (IPCC 2006).

What we don't know

The fine scale temporal and spatial changes of greenhouse gas emissions in response to management and different climatic conditions, remain difficult to predict. Measured emissions of greenhouse gases from hundreds of recent studies often vary significantly from those predicted by empirical modelling approaches such as those used by IPCC. Although such modelling approaches remain valuable tools in our ability to understand and mitigate emissions, further development of methodologies and modelling approaches is urgently required. This will help deliver more targeted and effective mitigation measures.

7. The impacts of land use change between dominant classes and potential impact of future change

What we know

There is considerable evidence that demonstrates land-use change in Scotland has the potential to contribute to a net removal of CO_2 from the atmosphere as it becomes locked up in soil organic matter over long periods of time. An analysis of recent trends shows that carbon uptake at the national level has increased from 2.3 Mt CO_{2e} in 1990 to 6.2 Mt CO_{2e} in 2014 (Fig. 2) mostly as a result of the creation of new forests. Literature gathered from Moxley *et al,* (2014) and Smith *et al* (2007) shown in Table 4 and 5 highlight evidence demonstrating gains in soil carbon through croplands and grasslands being converted to woodland. Soil carbon losses are reported for grasslands converted to croplands. In the case of cropland converted to grassland, Moxley *et al*, (2014) found results to be inconclusive as to whether there is a clear positive or negative effect whereas Smith *et al,* (2007) showed carbon uptake by the conversion of croplands to grasslands. Forests and grasslands are net sinks for soil carbon with croplands and settlements being net sources Salisbury *et al,* (2016).

Table 4. Changes in soil carbon following land use change, taken from Moxley *et al,* (2014).

Management Type	Description	Direction of change+	% Change in carbon stock	% Change in carbon conc++	Reference
Arable to Woodland	Reversion to deciduous woodland	+		~400	Kinchesh *et al.* (1995)
Cropland to mixed forest	soil carbon changes in landscape units of Belgium between 1960 and 2000	+	17.1		Lettens *et al*, (2005)
Cropland to broadleaf forest	soil carbon changes in landscape units of Belgium between 1960 and 2000	+	8.3		Lettens *et al*, (2005)
Cropland to coniferous forest	soil carbon changes in landscape units of Belgium between 1960 and 2000	+	1.1		Lettens *et al*, (2005)
Grassland to Woodland	After 20yrs of afforestation compared to grassland	+		23	Del Galdo *et al.* (2003)
Grassland to Cropland	Conversion of grassland to cultivated cropland in uppermost 20cm	-	50		Spohn & Giani (2011)
Cropland to Grassland	Conversion of cropland to grassland (Reshaped the soil carbon distribution)	\	~ -2-4		Don *et al.* (2009)
Cropland to Grassland	Long term agricultural use compared to permanent grassland	-		48	Del Galdo *et al.* (2003)
Cropland to pasture	soil carbon changes in landscape units of Belgium between 1960 and 2000	+	18.7		Lettens et al (2005)
Afforested vs Permanent woodland	Afforested plots compared to permanent forest soils	-		64	Spohn & Giani (2011)

+ Direction of change: positive gain in carbon (+), loss in carbon (-) or no/negligible change (\). ++conc refers to carbon concentration in the soil.

Table 5. Potential changes in soil carbon storage in terms of conversion of land uses, taken from Smith et al (2007).

Land Use Change	Net C rate[a] and uncertainty ($x10^3$ kg C ha^{-1} yr^{-1})	Reference
Arable to ley:arable rotation	1.6	Smith *et al.* (1997)
Arable to grassland (50yr)	0.3-0.8	IPCC (2000)
Arable to grassland (35yr)	0.63	Jenkinson *et al*, (1987)
Arable to grassland (15-25yr)	0.3-1.9 ± 0.6, 110%	Vleeshouwers & Verhagen (2002); Guo and Gifford, (2002); Murty *et al*, (2002)
Arable to grassland short ley (20yr)	0.35	Soussana *et al.* (2004)
Arable to permanent pasture	0.27	Post, (2000)
Arable to forestry (115yr)	0.52+1.53(C in veg)	Hooker, (2003)
Arable to forestry	0.62+2.8(C in veg)	Smith *et al*, (2000); Falloon *et al*, (2002)
Arable to forestry (25yr)	0.3-0.6, >50%	Guo, (2002);Murty, (2002)
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 to arable (20yr)	-0.95±0.3, 95%CI	Soussana *et al*, (2004)
Grassland to arable	-1.0 to -1.7, >50%	Smith *et al*, (1996); Guo and Gifford, (2002); Murty et al, (2002)
Grassland to afforestation (general, 90yr)	0.1±0.02, 95%CI	(Soussana *et al*, (2004)
Moorland to grassland	-0.9 to -1.1	Soussana *et al*, (2004)
Forestry to arable	-0.6	Guo, (2002);Murty, (2002)
Forestry to grassland	-0.1±0.1, 95%CI	Soussana *et al*, (2004)
Native vegetation to grassland	0.35	Conant, (2001)
Peatland to cultivation	-2.2 to -5.4	Freibauer, (2004)
Wetland restoration	0.1-1.0	Watson *et al*, (2000)
Revegetation on abandoned arable	0.3-0.6, >50%	Poulton *et al.* (2003)
Revegetation on wetland from arable	2.2-4.6, >50%	Kamp *et al*. (1997)
Revegetation on wetland from grassland	0.8-3.9, >50%	Kamp *et al*. (1997)
Conservation	>2.2, >50%	Freibauer *et al*, (2004)

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

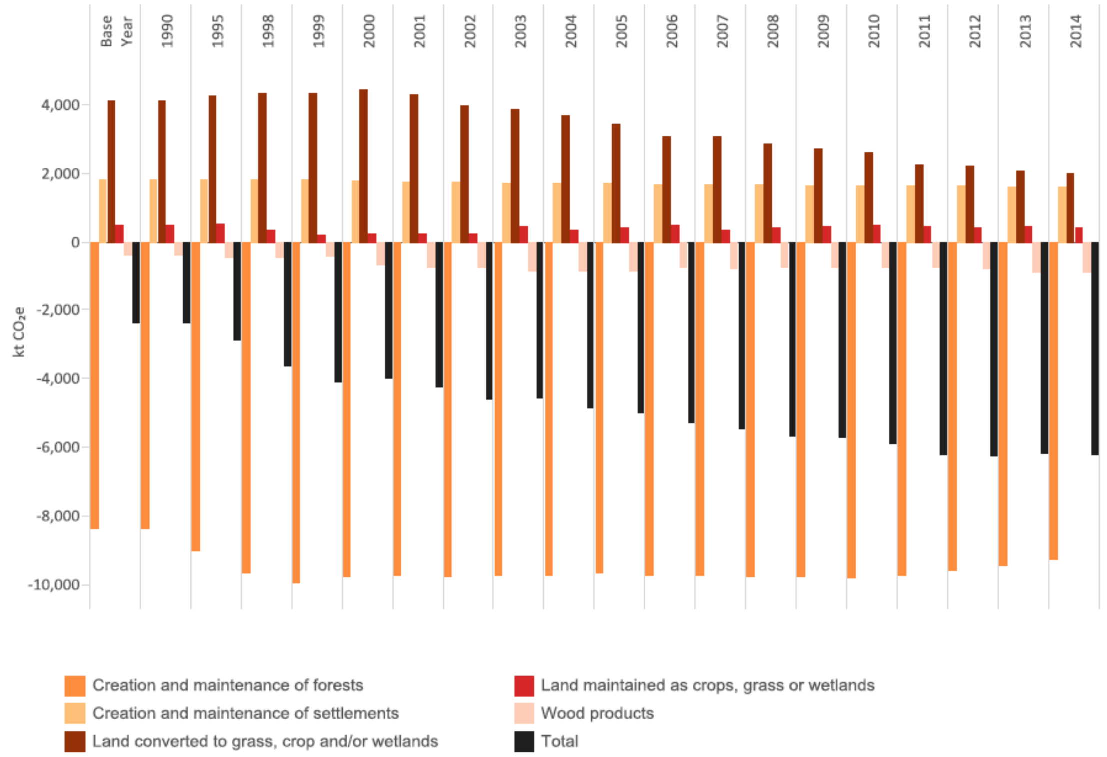

Figure 2. Emissions and removals of all gases by category for the LULUCF sector in Scotland 1990-2014. Salisbury *et al* (2016).

Areas that are subject to active research and debate (i.e. where there is uncertainty or ambiguity?)
While the evidence widely accepts that land-use change results in slow and long term changes in the carbon stocks of Scottish soils, quantifying such changes requires careful long-term research and modelling. There are a limited number of good experimental data to quantify uncertainty in this area. A particularly important area relates to rotational grass and arable farming systems which frequently cycle from one land-use category to another resulting in carbon stock changes that can be difficult to quantify.

What we don't know
There are presently insufficient measured data from a range of UK climate, land-use and soil type conditions to quantify with confidence soil carbon changes during afforestation. This is partly because of the difficulties of detecting relatively slow changes in spatially heterogeneous soils (Morison *et al*, 2012). After afforestation it is likely that on mineral soils, particularly those with low carbon contents due to previous long-term cultivation, there will be an increase of soil carbon, from soon after planting with rates of carbon accumulation in the range 0.2–1.7 t CO_2 /ha/year. (0.05–0.46 t C /ha/year) (Morison *et al*, 2012; Vanguelova and Pitman, 2010).

There is scant UK evidence on the soil carbon consequences of the afforestation of mineral soils, though data on the impacts of more gradual land-use change from arable to woodland exist. A long-term investigation exists at Rothamsted where arable land has reverted to acid soil woodland after being abandoned in 1886. Soil organic carbon (to 69 cm) increased from 29 t C/ha in the 1880s to 62 t C/ha in the 1980s (Poulton, 1996), with an average rate of accumulation in soil and litter of 0.38 t C /ha/year, or 1.4 t CO_2 /ha/year (Poulton, 2006). Similar rates of soil carbon accumulation, e.g. between 0.1-0.3 t /ha/year have been measured from long term soil carbon monitoring and compared with 200 years chronosequence data in broadleaved Oak forest on surface water gley soils (Benham *et al*, 2012). However, both studies are in lowlands in England and the drier and warmer climate compared to Scotland will inevitable influence the rate of carbon accumulation in mineral soil.

Restoration of degraded peatlands is recognised as an important opportunity to contribute to carbon sequestration. However, there are relatively few good studies that provide quantitative information on the amounts of carbon potentially stored and time periods over which this could take place.

8. The relative carbon impact of specific different land management practices on-the-ground

Only 25% of Scottish soils are cultivated for agriculture (including improved grassland) this is much lower than in most European countries. An additional 45 % is also used for agriculture for rough grazing. Chamberlain et al (2010) showed mean topsoil carbon stocks were measured at 619, 623 and 628 Mt carbon in 1978, 1998 and 2007 respectively, using Countryside Survey of Scotland, England and Wales data showing no significant difference over this period. Lilly and Baggaley (2013) estimate the amount of carbon stored in Scottish cultivated mineral soils is 246±9 Mt, but that there is a potential to increase this by between 150 and 215 Mt based on national scale legacy data with uncertainty around the estimate due to error terms predicting bulk densities for stock calculations. The State of Scottish Soils Report (Rees *et al.* 2011) highlights the potential for carbon sequestration in arable farming focused in south and east Scotland, which has lower organic matter (OM) resulting in much interest in managing soils to increase carbon in these areas. Effective management of agricultural soils can benefit CO_2 removal and carbon sequestration, reporting of which is allowable under Article 3.4 of the Kyoto Protocol (Smith, 2004). Types of agricultural management that have been reviewed in terms of carbon sequestration potential are outlined in Table **6** and discussed below.

Tillage: Disturbance and aeration of soil via tillage practices is widely believed to expose organic material to degradation and a loss of soil carbon. (West, 2002) concluded that a conversion of conventional tillage to zero tillage sequesters an average of 0.57±0.14 t C /ha/ year (to a maximum of 30 cm depth). However, more recent analyses of soil carbon to a 1 m depth have shown conventional and zero tillage only results in different distributions of soil carbon not additional storage (e.g. Baker *et al.* (2007) and Angers, (2008). These findings are not universal since studies contradicting this finding have been reported with a net and significant carbon sequestration under zero tillage despite the greater soil carbon content from conventional tillage at depth (e.g. Gal *et al.* (2007). However, the consensus view would now be that the application of reduced or zero tillage management in the UK has little net effect on carbon storage (Powlson *et al.* 2012).

Fertiliser use, yield and residue inputs: Most soil carbon is stabilized with a C:N ratio of approximately 10:1 indicating that if soil storage is to increase, nitrogen is also required to maintain this stable ratio of carbon to nitrogen. Effective fertilisation and improved crop rotation is known to increase crop yields and subsequent input of crop residue carbon to soils, leading to soil carbon accumulation (Fageria 2012; Snyder *et al.* 2009). Accumulation of carbon from nitrogen additions is considered to come from roots and root exudates during growth. Whilst root derived carbon is generally considered to make the largest relative contribution to total soil aggregate associated carbon, the reincorporation of residues (either total straw or stubble) to the soil will also tend to increase soil carbon as these residues form the basis for new soil organic carbon (Moxley et al., 2014). Manure applications provide carbon additions but may be considered to have limited potential for increasing soil carbon at the national scale due to the requirement of more livestock and implications for increased GHG emissions. There is evidence that manure application could be better targeted (e.g. Smith *et al.* (2008)). A recent Defra report (Moxley *et al.* 2014) indicated that since arable soils tend to have smaller soil carbon contents than grassland soils they will have greater potential for increased soil carbon storage. Evidence to support this is provided by Lilly and Baggaley (2013). There are few data available to quantify the effect of rotation on soil carbon increases in tilled soils in NW Europe and no specific reviews or meta-analyses were found (Moxley et al 2014). An increase in cropping intensity and/or crop rotations increase the quantity and quality of residues as well as providing an increase in soil carbon stocks compared with monocultures (Christopher, 2007). This finding may be more relevant to regions where fallow is practised and legumes may be included to increase yields of subsequent crops and hence be less applicable to Scotland and the UK.

Adding organic material (compost and manures) over an extended period of time can result in significant changes to soil carbon (King *et al.* 2004), but the contribution of different organic matter sources to the build-up of soil carbon will vary according to intrinsic properties of the material added and subsequent management of the soil (Jones, 2006). Priming (the stimulation of microbial activity) can increase decomposition in the short term resulting in increased CO_2 efflux following organic matter applications (as discussed by Kuzyakov & Bol (2006)). Overall good soil management which includes building soil fertility and the addition of organic substrates is known to increase the soil carbon pools (Rees *et al.* 2011). The extent to which there is further capacity to do this in Scotland is more uncertain, given that good management is generally already practiced.

Crop rotations: It is widely accepted that the elimination of bare ground over winter, either by cover cropping or increased volunteer (weed) growth increases soil carbon by several mechanisms. Increased carbon gain during the fallow season growth, especially during early autumn, reduces net carbon losses (Hollinger *et al*, 2005). Blomback *et al.* (2003) reported an increase in soil carbon of 2% after 6 years of continuous winter cover cropping in Sweden (when compared with no cover crop). Cover crops also increase water use, keeping soils drier longer, and reducing the rate of soil decomposition (Desjardins *et al*, 2005). However, when costs of establishment and destruction are taken into account, the economics of using cover crops to increase soil carbon may become unfavourable.

Extensification: Comparison has been made between relatively intensive management systems (those receiving high inputs fertilisers and energy) with more extensive systems that would be dependent on lower external inputs. Amman *et al.* (2009) compared extensive and intensively grassland and found that there was more carbon sequestration under the intensive management as a result of higher nitrogen inputs. Moxley *et al*. (2014) found intensively managed grasslands were able to sequester more carbon than extensive systems (Ammann *et al.* 2007), with the magnitude of this sequestration over 2 t C/ ha. These differences are likely to be due to differences in soil fertility which are known to drive carbon inputs to soil as described above.

Liming: Soil carbon was found to increase by 27 t/ha following lime applications to grassland in a study by Fornara *et al.* (2011) and Hopkins *et al.* (2009). However, this contradicts reviews where liming of organic rich pasture soils had the tendency to decrease soil carbon, most probably due to the soils studied being mineral soils classified as well-drained silty clay loams (soil organic-carbon contents around 3 %) with liming having an influence on the solubility of soil organic-carbon. Liming makes an important contribution to maintaining productivity in grasslands and by doing so indirectly contributes to carbon sequestration. However, given the carbon losses that result directly from lime application (which offset soil carbon gains), it would be difficult to recommend liming as a measure for increasing carbon sequestration.

The overall effectiveness of agricultural management to contribute to soil carbon storage depends on the interaction of management practices with soil and climatic characteristics. We know that drained sandy soils that are used for arable cropping have limited capacity for increased carbon storage which is related to low clay contents and the ease with which organic carbon that is added to these soils is vulnerable to loss through microbial decomposition (Loveland, 2003). Other land uses such as forestry and grasslands tend to have higher soil carbon contents, however, maintaining these carbon pools may be a more appropriate policy objective than attempting to increase carbon content of existing soils. Protection of soil from erosion, the loss of permanent plant cover, and drainage organic soils and peatlands are particularly important in this context.

Table 6. Summary of the affects of agricultural management practices on carbon sequestration.

Management	Authors	t C /ha/year
Zero tillage	West and Post, (2002)	0.57 ± 0.14
	Baker et al., (2007)	0
	Smith et al., (2008)	0.05-0.21
	Angers and Eriksen-Hamel (2008)	0.28
	VandenBygaart et al., (2008)*	0.06-0.10
	Luo et al. (2010)	0
(Reduced tillage)	Hutchinson et al., (2007)	0-0.4
Increase forage in rotation	Hutchinson et al., (2007)	0-0.5
	Smith et al., (2008)	0.1 - 0.3
	Smith et al., (2008) (legumes)	0.1 - 0.2
Increase yields and residue return	Hutchinson, (2007)	0-0.3
Use organic materials more efficiently	(Smith 2008)	0.5 - 0.8
	Hutchinson et al., (2007)	0.1-0.5
Organic manures to cropland rather than grassland	Smith et al., (2008)	0.5 - 0.8
Improved grazing practices	Hutchinson et al., (2007)	0-0.1
Increase grassland productivity	Hutchinson et al., (2007)	0-0.3
	Amann et al., (2007)	>2.0
Catch crops	Smith et al., (2008)	0.1-0.3
Residue management	Smith et al., (2008)	0.05-0.21
Grassland extensification	Smith et al., (2008)	0.5 - 0.9

Forest management:

Afforestation of land previously used for agricultural purposes provides the greatest potential for increasing soil carbon storage. If the forest mineral soil is of high clay texture, most of the sequestered carbon (70%) will be in a stable form (Villada *et al*., 2013), thus aiding long term carbon storage in the soil. In addition, mineral soils under forestry can be a potential methane sink. However, there is a limited amount of research that shows where forests are planted on organo-mineral soils, they may alter the soil sequestration potential due to soil disturbance and forest management and the sensitivity of the organo-mineral soil to carbon loss. Organic soils already high in soil organic carbon provide less opportunity for the storage of additional carbon through afforestation.

Areas that are subject to active research and debate (i.e. where there is uncertainty or ambiguity)
Many of the changes in agricultural management practices described in this report are considered to have the potential to increase soil carbon stocks, and this potential has also been recognised in the analysis by Lilly and Baggaley (2013). However, such changes would be unlikely to be identified in national inventory reports and would therefore not be viewed as contributing to government targets for GHG mitigation. This is because the current inventory is insensitive to changes in carbon stocks resulting from altered management of agricultural land (i.e. without land use change). Further development of reporting procedures is therefore required.

While recent years have seen an increase in research effort in measuring GHG fluxes from Scottish peatlands in various conditions (Table 7), it is necessary to consider UK-wide data in order to have a sufficient number of representative sites. Even with this extension, in many cases the values returned are based upon limited spatial data obtained over a limited timespan with the result that values carry a high degree of uncertainty.

Work is ongoing in trying to establish better emission factors for the UK, including the most recent findings, so as to meet IPCC requirements for Tier 2 factors (Artz *et al.* 2015; Evans *et al.* 2014a; Evans *et al.* 2014b; Wilson *et al.* 2015). It is expected that the findings of a DECC-funded project, which will collate both the historic and the most recent UK-relevant data, will be published later in 2016.

Table 7. Emission factors (mean ± standard error, t CO_{2e}/ha/year) for four different peatland condition categories as used in the UK Peatland Code, after Dickie et al. (2015).

Peatland Condition Category	Code	CO_2	CH_4	N_2O	DOC	POC	Emission Factor
Near natural		-3.0±0.7	3.2±1.2	0.0±0.0	0.88	0	1.1
Modified		-0.1±2.3	1.0±0.6	0.5±0.3	1.14	0	2.5
Drained		1.4±1.8	2.0±0.8	0.0±0.0	1.14	0	4.5
Actively Eroding		2.6±2.0	0.8±0.4	0.0±0.0	1.14	19.3	23.8

What we don't know
There are considerable uncertainties regarding the impacts of climate change on changes in carbon storage that will occur as a consequence of management within land use categories. It is anticipated that there would be a strong interaction between climate and management that needs to be better defined.

9. Conclusion

Extensive studies and monitoring of Scotland's soils has demonstrated that they are rich in carbon, containing a total of around 3000 Mt which is more than half of the UK's total soil carbon stock, much of which is stored in the organic peaty soils located in the north and west of the country. This makes Scottish soils important carbon stores on an international basis. We know that the Scottish landscape acts as a net sink for carbon, removing $CO_2$from the atmosphere and storing it in soils at a rate of 10 Mt /year. However, we also know that there is significant variability between different land uses, with most carbon uptake occurring within forests. There are some opportunities for agricultural land management to increase carbon storage although for the purposes of greenhouse gas mitigation greater opportunities exist to reduce the non-CO_2 greenhouse gases (nitrous oxide and methane). The large existing stocks of carbon also highlight the importance of measures to avoid carbon loss from soils.

The largest opportunities to use land management to or remove CO_2 from the atmosphere provided by the restoration of degraded peatlands which could contribute to removing between 0.6-8.3 Mt CO_{2e}/year. There is however, a need to improve inventory reporting to better reflect the potential carbon sequestration by soils resulting from improved management.

There is considerable uncertainty about how climate management and future land use will interact to affect soil carbon stocks in the coming decades. Scottish Government's Strategic Research programme (2016 to 2021), and related research funded by the U.K.'s research councils is actively investigating these issues using measurement and modelling approaches. Warmer and wetter climates would be likely to increase the productivity of both natural and managed ecosystems, which would increase CO_2 uptake. However, such climates also have the potential to increase the breakdown of soil organic matter through soil respiration releasing CO_2 to the atmosphere. The outcome of these changes and what management responses develop in order to accommodate them are finely balanced, but would be certain to influence the long term trajectory of soil carbon stocks.

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