

CLIMATE-POSITIVE FARMING REVIEWS



The James
Hutton
Institute

A review of the effects of land use and land management changes on soil organic carbon stocks in hill farms



Allan Lilly, Nikki Baggaley, Jagadeesh Yeluripati

September 2020

Aberdeen
Craigiebuckler
Aberdeen AB15 8QH
Scotland UK

Dundee
Invergowrie
Dundee DD2 5DA
Scotland UK

Tel: +44 (0)344 928 5428
Fax: +44 (0)344 928 5429
info@hutton.ac.uk
www.hutton.ac.uk



Executive Summary

This report summarises what is known about the potential impacts of changing land uses on soil organic carbon (SOC) stocks in Scottish hill farms, using the farm of Glensaugh as an exemplar. The soils, climate and topography determine the current land use and the potential for land use change. As much of the land of Scotland has soil with organic surface layers, there is considerable scope for SOC losses and perhaps less scope for net gains. From the review of current literature, there is limited data for many of the potential changes. We have indicated likely directions of change based on expert knowledge, even if there are insufficient data available for quantification. A more detailed and systematic review of the literature that specifically pertains to the soil types found in Scotland and Glensaugh may be able to determine rates of change rather than simply direction of change. This would allow a more detailed examination of the offset, or otherwise) of biomass production and the overall GHG balance.

Key findings from the review include:

- land use changes from grassland to arable, particularly at depths >30cm (Li *et al.*, 2020): most report that conversion of grassland to arable land will lead to a loss of SOC.
- experimental data show that the rate of potential increases in grassland SOC stocks following changes in intensity of grassland management slows over time.
- conversion from extensively grazed grassland with poor quality grasses and dwarf shrub vegetation to intensively managed grassland will result in a loss of SOC.
- planting trees on organo-mineral soils is shown to result in net GHG emissions.
- GHG mitigation measures will need to identify management practices that maintain or sequester carbon in soil while also reducing other GHG emissions.
- there remains a considerable gap in our knowledge of the status of SOC concentration and stocks for large areas of Glensaugh Farm and for the different land uses.

Contents

| | |
|---|----|
| Executive Summary | 1 |
| List of tables..... | 2 |
| List of Figures..... | 3 |
| Introduction..... | 4 |
| The soils of Scottish hill farms | 4 |
| The soils of Glensaugh..... | 4 |
| Estimates of current soil organic carbon (SOC) stock for Glensaugh..... | 6 |
| Comparison with measured stocks | 8 |
| Land use changes and their potential impacts on SOC stocks | 10 |
| Potential land use changes..... | 10 |
| Potential impacts on SOC stocks due to land use changes | 12 |
| Land use changes from intensively managed grasslands..... | 13 |
| Land use changes from extensively managed grassland and moorland | 15 |
| Land use changes from forestry/woodlands..... | 17 |
| Other land use changes, e.g. restoration of peatland..... | 17 |
| Estimating net GHG emissions for a farm unit | 18 |
| Conclusions..... | 18 |
| References: | 21 |
| Appendix 1: SOC stocks at Glensaugh by depth..... | 26 |
| Appendix 2: Rotational mob grazing regime at Glensaugh..... | 28 |
| Appendix 3: Direction of change in SOC stocks by land use..... | 29 |

List of tables

| | |
|---|----|
| Table 1. Current soil and land use combination and areal extent (ha) at Glensaugh, derived from GIS overlay of 1:25,000 scale digital soil map of Scotland (partial cover) and IACS (Integrated Administrative and Control System) land use data..... | 5 |
| Table 2: Current estimated total soil organic carbon stock to 100 cm depth for Glensaugh (t)..... | 7 |
| Table 3: Current estimated area-weighted soil organic carbon stock to 100 cm depth (t C ha ⁻¹) for Glensaugh..... | 8 |
| Table 4: Proportion of mineral topsoil (0-30cm depth) SOC lost during ground preparation for afforestation (West <i>et al.</i> , 2011). | 14 |
| Table 5: Estimate proportion of organo-mineral topsoil (0-30cm depth) SOC lost during ground preparation for afforestation (source: West, 2011)..... | 16 |
| Table 6: Likely direction of change of net GHG emissions due to a change in Land use, colour-coded by soil type (see key below table)..... | 20 |

List of Figures

| | |
|---|----|
| Figure 1: Distribution of the major soil subgroups at Glensaugh Farm derived from the phase 7 Soil map of Scotland (partial cover). Soil Survey of Scotland staff (1970-1987) | 6 |
| Figure 2: Comparison of measured SOC stocks from previous studies against SOC stocks estimated from data held in Scottish Soils Database for selected Glensaugh soils. | 8 |
| Figure 3: Distribution of major soil subgroups and sample points with calculated SOC stocks at Glensaugh (Soil Survey of Scotland Staff (1970-1987) | 10 |
| Figure 4: Distribution of major soil subgroups and sample points with measured SOC concentrations at Glensaugh (Soil Survey of Scotland Staff (1970-1987) | 10 |
| Figure 5: Land Capability for Agriculture classification for Glensaugh Farm (Soil Survey of Scotland staff (1984-87))..... | 12 |
| Figure 6: Land Capability for Forestry classification for Glensaugh Farm (Soil Survey of Scotland staff (1989)).... | 12 |

Introduction

There is growing interest world-wide in using soil (and land use change) to remove CO₂ from the atmosphere, indeed Article 3 of the Kyoto protocol specifically addresses this. Where much of the focus was on forestry, subsections of the Article also set out the role that cropland and grazing land management alongside revegetation could play in reducing atmospheric CO₂ and potentially limiting other Green House Gases (GHGs) such as N₂O. The Committee on Climate Change (CCC) in their assessment of the first Scottish Climate Change Adaptation Programme (SCCAP) in 2019 stated that *'changes in carbon stored in soils will have a more significant impact on priority habitats and provisioning of ecosystem services in Scotland than the rest of the UK'* thereby acknowledging that soils can both be a sink and a source of GHGs.

Data from the 5km National Soil Inventory of Scotland show that around 60% of Scottish soils have an organic surface layer that typically has > 40% organic carbon and are uncultivated while 24% of Scottish soils have both a mineral topsoil and are cultivated, and have typical topsoil carbon concentrations between 2 and 5% (Scottish Soils Database). Clearly there is a significantly greater risk of increasing GHG emissions and losses of soil carbon from organic and organo-mineral soils typically found in hill farms of the uplands than from mineral soils due poor land management, land use or climate change. However, much of the focus in the literature is on soil carbon sequestration in those soils under highly managed, cultivated arable and improved pastures.

The soils of Scottish hill farms

While the proportion of soil types and land uses will vary between farms, in general they will tend to have a small proportion of cultivated mineral and alluvial soils around the steading with a larger proportion of uncultivated organo-mineral and organic soils used for extensive grazing of sheep and cattle. At a national scale, these uncultivated upland organic (peat) and organo-mineral soils (mainly peaty gleys, peaty gleyed podzols and humus iron podzols) occupy 22% and 32% of Scotland respectively and hold around 2100 Mt carbon in the upper 100 cm which could be released as CO₂ if these soils were mismanaged. The organo-mineral soils have more than half (501 Mt) of their carbon stored in the upper organic layer and 918 Mt in total to 100 cm depth. The cultivated mineral soils in contrast, occupy 24% and hold only just over 400 Mt C within the upper 100 cm, with over half (250 Mt) held in the topsoil. Other soil types, for example, rankers, lithosols or arctic soils make up the remainder of Scotland's estimated 3000 Mt soil carbon (Baggaley *et al.*, 2016).

The soils of Glensaugh

The James Hutton Institute's Glensaugh research farm provides an exemplar of the soils, land uses and land use opportunities for hill farms in Scotland. Glensaugh comprises around 1000 ha of largely hill land, and has been selected to explore, test and demonstrate transformational methods of sustainable land management that provide multiple benefits whilst reducing the carbon footprint of the farm. This review summarises the current soil organic carbon (SOC) stock of the farm under the different land

uses and explores the impact on SOC stocks (and to a lesser extent GHG emissions) of plausible land use changes and land management practices.

Like many UK hill farms, Glensaugh comprises a mixture of uncultivated organic (peat), organo-mineral and cultivated mineral soils. The mineral soils (22%) are primarily concentrated around the farm steading and lower slopes, lying at altitudes of between 110 and 250 m (above ordnance datum). These soils are primarily brown earth (free and imperfectly drained), cultivated humus-iron podzols and noncalcareous gleys with some alluvial soils. Between 250 m and approximately 400 m, the soils comprise uncultivated, organo-mineral peaty gleyed podzols (28%), humus-iron podzols (27%) and a small proportion of peaty gleys (2%). These soils have an anaerobic (or aerobic in the case of the humus-iron podzols) organic surface layer < 50cm thick with typically between 40 and 50% organic carbon and largely support a semi-natural vegetation of dwarf shrubs and grasses. At altitudes greater than 400 m, the dominant soil type is peat (21%). These organic soils have organic layers greater than 50 cm thick (depths over 300 cm have been recorded on the farm) and carbon concentration around 50%. The peat soils also support semi-natural vegetation dominated by dwarf shrubs (Figure 1).

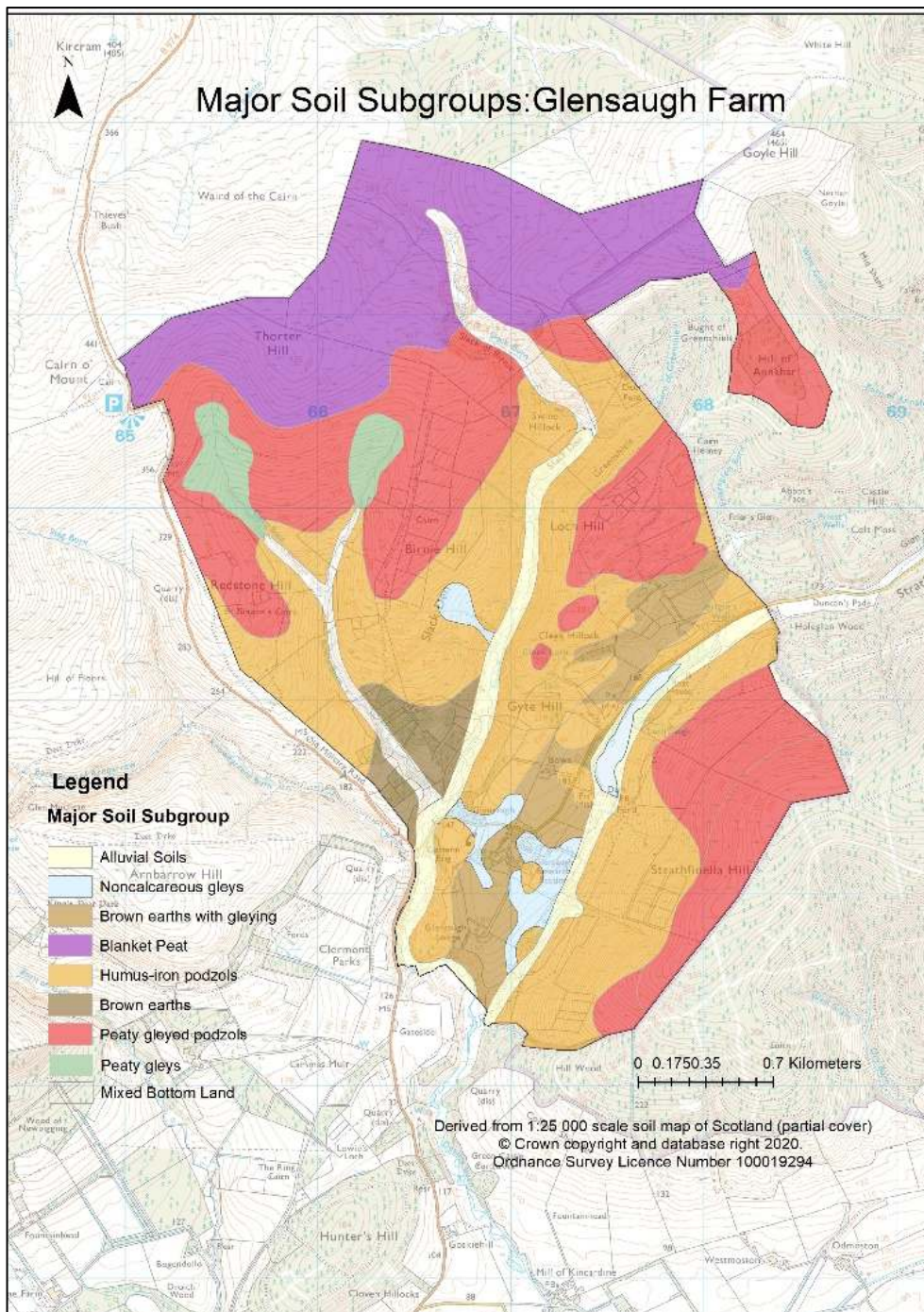
The mineral and organo-mineral soils on Glensaugh belong to the Strichen and Strathfinella Associations with the former occupying the land north of the Highland boundary fault and those of the latter occupying the land on the lower slopes of Strathfinella Hill. The soils of both associations tend to be acidic in nature as the parent materials are derived from acid igneous and metamorphic rocks with Strathfinella Association soils also having a component of Lower Old Red Sandstone aged sediments. As well as semi-natural dwarf shrubs and grasses on the organic and organo-mineral soils and improved grassland on the mineral soils, the land cover also includes areas of agroforestry and forestry on both organo-mineral and mineral soils (Table 1).

Table 1. Current soil and land use combination and areal extent (ha) at Glensaugh, derived from GIS overlay of 1:25,000 scale digital soil map of Scotland (partial cover) and IACS (Integrated Administrative and Control System) land use data.

| Soils | Land use (ha) | | | |
|---------------------------|------------------------------|-------------------|--------------|----------|
| | Intensive grazing/break crop | Extensive grazing | Agroforestry | Forestry |
| Peat | - | 197 | - | - |
| Peaty gleys | - | 23 | - | - |
| Peaty gleyed Podzols | 43 | 222 | - | - |
| Humus iron podzols (uc) | - | 243 | - | 19 |
| Humus iron podzols (c) | 38 | - | 1 | - |
| Noncalcareous gleys | 12 | 4 | - | 2 |
| Brown earths | - | 4 | 17 | 1 |
| Brown earths with gleying | 35 | 12 | - | 3 |
| Alluvial soils | 7 | 63 | 2 | 7 |

(uc) = uncultivated; (c) = cultivated; - combination does not occur

Figure 1: Distribution of the major soil subgroups at Glensaugh Farm derived from the phase 7 Soil map of Scotland (partial cover). Soil Survey of Scotland staff (1970-1987).



Estimates of current soil organic carbon (SOC) stock for Glensaugh

The stock of SOC to a depth of 100 cm was determined for each of the soil/land use combinations based on data held within the Scottish Soils Database for the specific soil types (Soil Series) found at Glensaugh and grouped at a major soil subgroup level (Table 2). Mean carbon concentrations were calculated for each soil horizon (layer) found in a typical profile of the soils found at Glensaugh. These

values were multiplied by the predicted bulk density based on regression equations developed for Scottish soils and by the horizon thickness to derive a SOC stock estimate for each horizon (Baggaley *et al.*, 2016). These values were then summed to 30 cm and 100 cm depth to give a total SOC stock in tonnes (t) and multiplied by the extent of each soil and summed by major soil subgroup. The total soil organic carbon stock to 1m depth was calculated as 271,572 t C of which 45% is stored within peat and a further 44% in organo-mineral soils with the remainder stored within mineral soils. Scottish mineral soils are relatively rich in SOC compared to other European countries and soils under long-term pasture are particularly rich in SOC with average values calculated from data held within the Scottish Soils Database of 5.15%. Lilly *et al.* (2020) calculated average SOC concentration of 4.48% for 37 topsoils in North-east Scotland. Whilst increasing SOC concentrations can have benefits in some mineral soils by improving aggregate stability, infiltration and water holding capacity, Chapman *et al* (2013) and Lilly and Chapman (2015) showed that measuring only change in SOC concentration can be misleading. They found a decline in SOC concentrations over time within cultivated mineral soils but found no change in stocks due to changes in topsoil horizon thickness (and possibly associated changes in bulk density). Changes in the thickness of organic layers rather than SOC concentrations are particularly important in determining SOC stocks and stock changes in organic and organo-mineral soils as the carbon concentration in these soils is relatively stable at around 40-50% C; and any loss (or gains) can only be seen through changes in the thickness of the layer.

The area-weighted SOC stock held by each major soil subgroup (t C ha⁻¹) is shown in Table 3. It is likely that these values are slight underestimates for mineral soils under woodland as the depth and density of the litter layers are unknown.

Table 2: Current estimated total soil organic carbon stock to 100 cm depth for Glensaugh (t).

| Soils | Intensive grazing/break crop | Extensive grazing | Agroforestry | Forestry |
|---------------------------|------------------------------|-------------------|--------------|----------|
| Peat* | - | 121,536 | - | - |
| Peaty gleys | - | 6,188 | - | - |
| Peaty gleyed podzols | 10,213 | 49,880 | - | - |
| Humus iron podzols (uc) | - | 48,380 | - | 3,821 |
| Humus iron podzols (c) | 5,338 | - | 223 | - |
| Noncalcareous gleys | 1,725 | 756 | - | 276 |
| Brown earths | 6 | 710 | 2,437 | 137 |
| Brown earths with gleying | 4,532 | 1,734 | - | 407 |
| Alluvial soils | 945 | 11,036 | 202 | 1,270 |

(uc) = uncultivated; (c) =cultivated; - combination does not occur: Mt is 1,000,000 tonnes

* Upland blanket peat

Table 3: Current estimated area-weighted soil organic carbon stock to 100 cm depth ($t\ C\ ha^{-1}$) for Glensaugh

| Soils | Intensive grazing/break crop | Extensive grazing | Agroforestry | Forestry |
|---------------------------|------------------------------|-------------------|--------------|----------|
| Peat | - | 616 | - | - |
| Peaty gleys | - | 273 | - | - |
| Peaty gleyed podzols | 239 | 225 | - | - |
| Humus iron podzols (uc) | - | 199 | - | 206 |
| Humus iron podzols (c) | 139 | - | 160 | - |
| Noncalcareous gleys | 143 | 181 | - | 181 |
| Brown earths | 140 | 188 | 140 | 188 |
| Brown earths with gleying | 129 | 149 | | 149 |
| Alluvial soils | 257 | 354 | 257 | 354 |

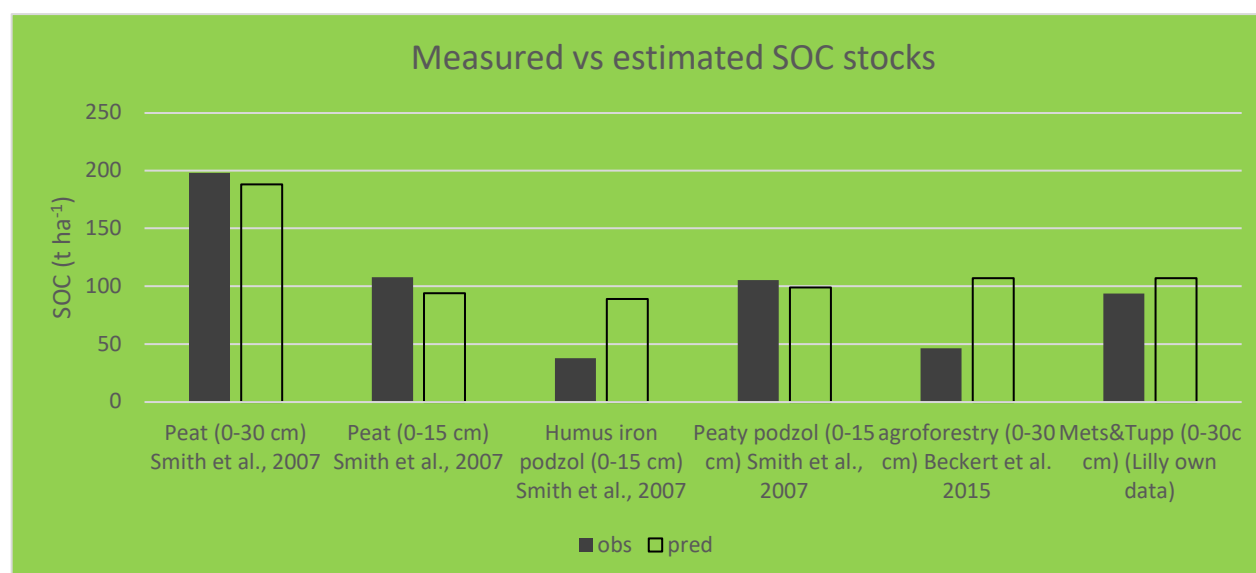
(uc) = uncultivated; (c) =cultivated; - combination does not occur

* Upland blanket peat

Comparison with measured stocks

A few studies at Glensaugh (e.g. Smith *et al.* 2007; Beckert *et al.* 2015) have quantified SOC stocks based on direct measurement of soil bulk density, horizon thickness and C concentration and can be used to partially validate the stocks estimated from data held on each soil type within the Scottish Soils Database (Figure 2).

Figure 2: Comparison of measured SOC stocks from previous studies against SOC stocks estimated from data held in Scottish Soils Database for selected Glensaugh soils.



Peats:

As part of a study to predict the impacts of changes in land use and climate change on GHG emissions from organic soils in both Scotland and Wales, and to validate the ECOSSE (Estimating Carbon in Organic Soils - Sequestration and Emissions) model (Smith *et al.* 2007), three 1 km² grid cells were sampled from the organic and organo-mineral soils found on Thorter Hill in the north-west part of Glensaugh (Figure 3). The depth of the organic layer was determined (up to a maximum of 300 cm), SOC concentration and bulk density at three depths (0-15, 15-30 and 50-65 cm) on a 200 m grid. The mean measured SOC stock for the peat was 107.7 t ha⁻¹ and 197.9 t ha⁻¹ for the depth range 0-15 cm and 0-30 cm respectively compared to the estimated stock of 94 and 188 t ha⁻¹ (Figure 2) suggesting that the SOC stock estimated from national data is representative of the actual stocks at Glensaugh.

Organo-mineral soils:

Some of the soils on the lower slopes of Thorter Hill are organo-mineral soil (mainly uncultivated humus-iron podzols and peaty podzols with some peaty gleys). As the organic layer is generally thinner than 30 cm in uncultivated humus-iron podzols, the measured SOC stocks between 0 and 15 cm depth were compared to the estimated stock (see Appendix 1 and Figure 2). The humus-iron podzols on Thorter hill had calculated SOC stocks of 37.8 t ha⁻¹ compared to an estimated value of 89 t ha⁻¹ and the peaty podzols had an average of 105.4 t ha⁻¹ compared to estimated value of 99 t ha⁻¹. The thickness of the organic layer in the Thorter hill humus-iron podzol was greater than 15 cm thick whereas the soil data used to estimate the SOC stock had organic layers of 10 or 11 cm thick overlying a leached mineral layer with only 5-6% organic carbon.

Mineral soils:

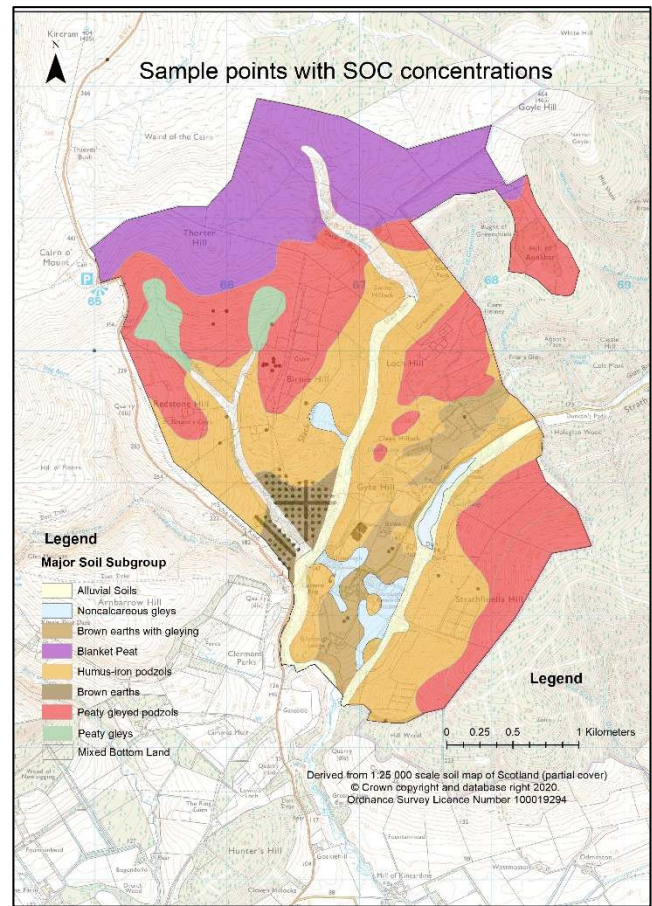
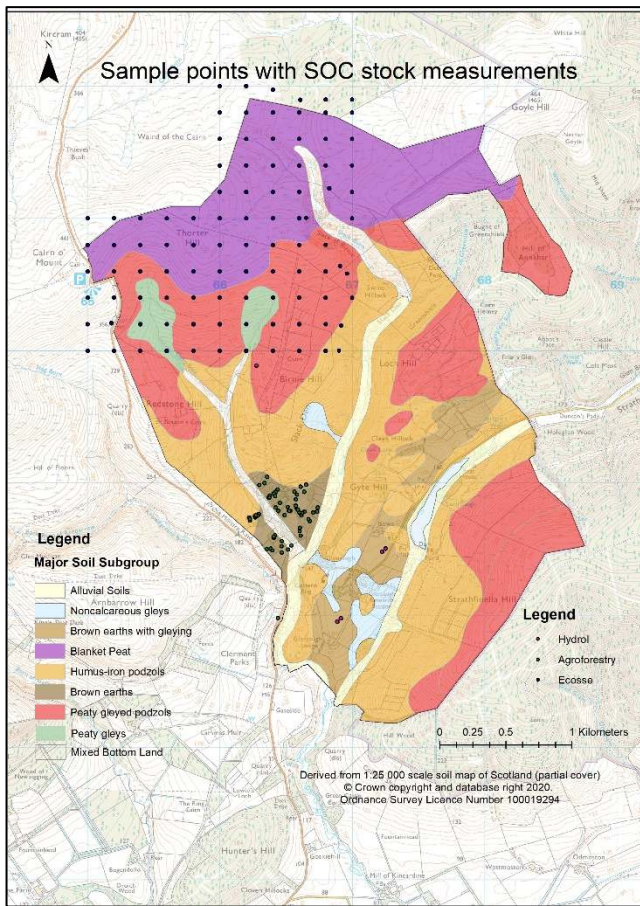
Soil samples have been taken from the agroforestry plots (Beckert *et al.* 2015) to assess change in SOC stocks over time and from both Mets and Tupp fields which are under intensively managed grassland. The soils in these sites are predominantly freely or imperfectly drained Brown earths. The average measured SOC stock to 30cm depth for the agroforestry site is 46.4 t ha⁻¹ compared to estimated values of 107 t ha⁻¹ (see Appendix 1 and Figure 2) but the average for the Mets and Tupp fields was 93.62 t ha⁻¹ compared to estimated values of 108 t ha⁻¹. The average bulk density of the agroforestry plot samples was 0.54 g cm⁻³ and the bulk density for the Mets and Tupp field sample was 0.79 g cm⁻³. The estimated bulk densities used to calculate the estimate SOC were based on data collected primarily from grassland and arable fields and are generally greater than those found in the agroforestry plots.

Summary:

The SOC stocks estimated based on data for the soils present at Glensaugh Farm and held within the Scottish Soils database are similar to measured data from samples taken from the farm (Figure 3) for peat and organo-mineral soils and those mineral soils under pasture. The biggest difference was between the estimated SOC stocks and measured data from the agroforestry plots. **However, there remains a considerable gap in our knowledge of the status of SOC concentration and stocks for large areas of the farm and for many of the different land uses (Figure 4).**

Figure 3: Distribution of major soil subgroups and sample points with calculated SOC stocks at Glensaugh (Soil Survey of Scotland Staff (1970-1987)

Figure 4: Distribution of major soil subgroups and sample points with measured SOC concentrations at Glensaugh (Soil Survey of Scotland Staff (1970-1987)



Land use changes and their potential impacts on SOC stocks

Potential land use changes

The potential range of land use changes in Scottish hill farms are limited to an extent by the climate, soils and topography as shown by the Land Capability classifications. The current SOC stocks at Glensaugh are a function of natural soil development, land use and land management. Using data from IACS (Integrated Administrative and Control System), National Forest Inventory (Forestry Commission) and Ovando (2020), the dominant land uses at Glensaugh were identified as intensively managed improved pasture, extensively managed rough grazing comprising grasses and dwarf shrubs (heathers), broadleaved, coniferous and mixed woodland and agroforestry (Table 3). The managed grassland is ploughed occasionally and a new grass crop sown. It receives organic and inorganic fertiliser annually, and lime is applied when required, to help maintain the sward as desired. The Extensively managed rough grazing (also known as moorland) comprises areas dominated by dwarf shrubs (heathers) and grasses such as *Molinia*, *Nardus*, *Agrostis* and fescues and it comes under the ‘Grassland’ category for IPCC Land use, Land Use Change and Forestry (LULUCF) Inventory for UK GHG reporting purposes (for example see Moxley *et al.*, 2014).

The Land Capability for Agriculture (LCA) maps of the farm (Figure 5) show an area of Class 3, division 2 land south-west of the steadings on imperfectly drained brown earths and poorly drained noncalcareous gleys indicating that some of the land is capable of growing arable crops such as barley and oats and break crops for winter fodder. It also suggests that the land has the potential to grow bioenergy crops, thus a land use change from intensively managed grassland to arable cropping is possible on this land.

The remaining areas of Glensaugh have limitations (climatic or soil) that restrict the agricultural land use to rough (extensive) grazing with few inputs to improve sward quality. The land on Finella Hill has been classed mainly as LCA class 5 (divisions 2 and 3) indicating that some grassland improvement is possible but may be difficult to maintain due to the peaty surface layers. The land to the north towards Thorter Hill is variously classed as LCA class 4 (mainly division 2) and some LCA class 3 division 2 on the agroforestry plots on Redstones. There is also some class 5 division 3 land on humus-iron and peaty podzols and class 6 divisions 2 and 3. Class 6 division 2 vegetation contains more nutritious grasses than division 3 which is predominantly dwarf-shrub vegetation communities and is primarily found on the peat on the top of Thorter Hill and on the land to the north east.

While the LCA mapping was originally undertaken at a 1:50 000 scale prior to digitising, the Land Capability for Forestry (LCF) mapping was only done at a reconnaissance 1:250 000 scale so the LCF map for the Farm shows less detail than the LCA and has no divisions of the classes (Figure 6). The land with the greatest potential for growing trees (class 4) is found on the imperfectly drained Brown earths and poorly drained noncalcareous gleys. This area has the potential to grow a range of coniferous trees and also less-demanding broadleaved tree species (Bibby *et al.* 1988). The largest proportion of the farm is in LCF class 5 (416.4 ha) and includes much of Finella Hill, the podzolic soils on the lower slopes of Thorter Hill and the agroforestry plots. This land is primarily capable of producing conifers and hardy broadleaved trees. Of the remaining land, 257 ha are in LCF class 7 with much (80%) of this coinciding with the peat soils where there is a presumption against planting trees due to the adverse impact on SOC stocks. A further 183 ha is in LCF class 6 which is land capable of growing a limited range of conifers such as lodgepole pine and Sitka spruce with some amenity broadleaves such as birch (Bibby *et al.*, 1988).

Figure 5: Land Capability for Agriculture classification for Glensaugh Farm (Soil Survey of Scotland staff (1984-87))

Figure 6: Land Capability for Forestry classification for Glensaugh Farm (Soil Survey of Scotland staff (1989))

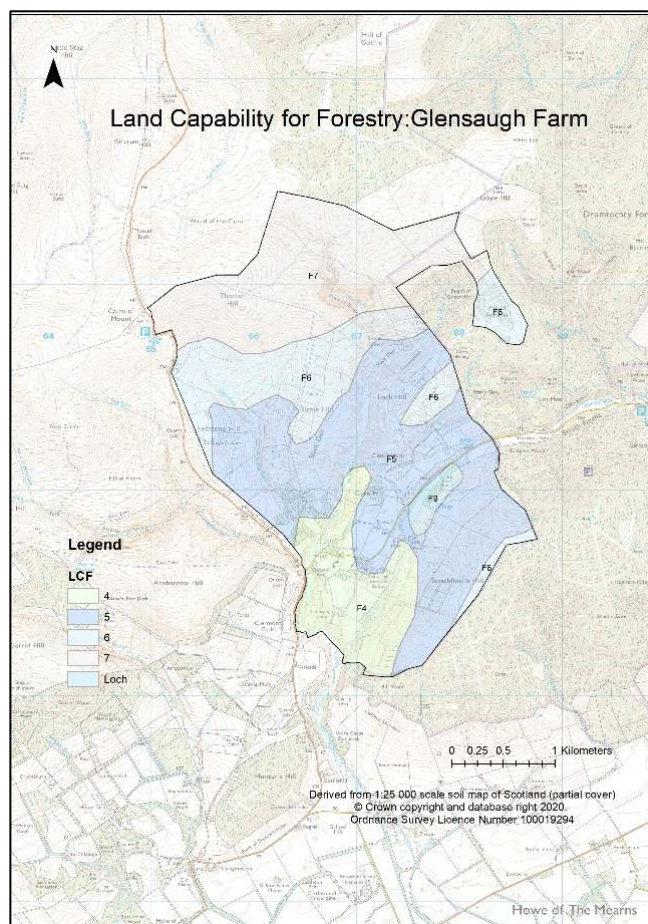
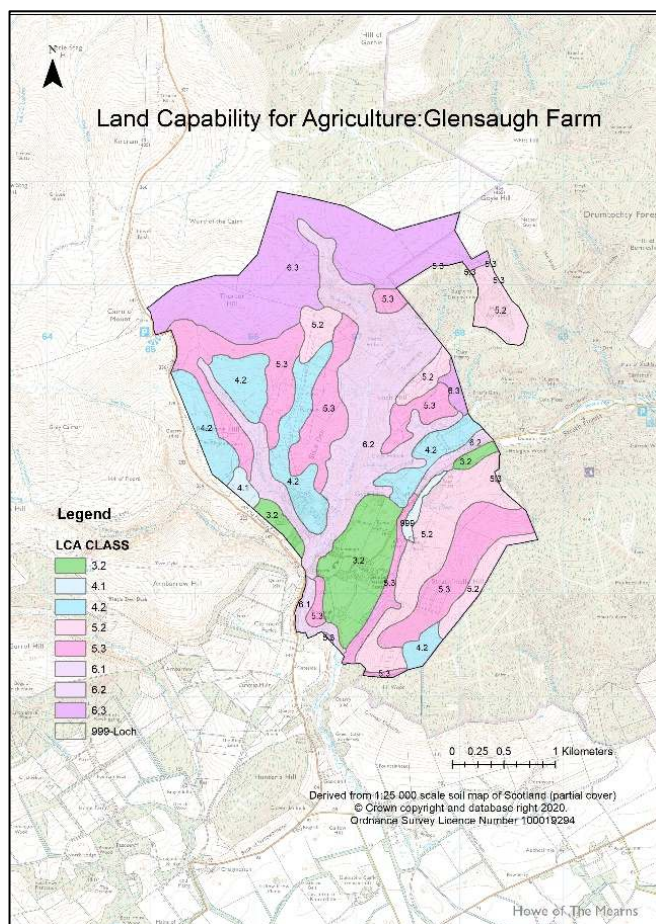


Table 3 shows the soil and land use combinations where intensive grazing/break crop represents the IACS category of ‘Permanent grassland’, ‘Extensive grazing’ represents IACS category of ‘Rough grazing’; and ‘Forestry’ represents ‘Woodland’.

Potential impacts on SOC stocks due to land use changes

In order to evaluate the likely direction of change in SOC stocks due to plausible land use changes, a literature review was undertaken to update some previously published reviews (Rees *et al.*, 2018; Moxley *et al.*, 2014; Smith *et al.*, 2007). Much of the recent literature reviewed were themselves meta analyses of numerous publications (e.g., Deng *et al.*, 2016; Tang *et al.*, 2019; Stefano and Jacobsen, 2018; Chatterjee *et al.*, 2018, Li *et al.*, 2020). Given the vast number of papers and reports available, this current review only considers the direction of change in SOC stocks (increase or decrease) rather than trying to assess the rate of change (Appendix 1). A more in-depth review of the literature would be required to identify or estimate rates of change. However, much of the rates published in the literature were for sites with sub-tropical, tropical or arid climates or land use changes not relevant to the soils found at Glensaugh, for example, there were few papers or reports detailing changes in organo-mineral soils. Note that changes from arable cropping to intensively managed grassland, extensively managed grassland, agroforestry, forestry and short rotation coppice are

included in Appendix 1 for information only. The remainder of this section of the report concentrates on changes from current land uses at Glensaugh to other potential land uses as identified above.

Land use changes from intensively managed grasslands

Around 135 ha of land at Glensaugh is currently under intensively managed grassland and has the greatest potential for change to alternative land uses.

Changes in level of intensification of the grassland. Fornara *et al.* (2020) showed that increased intensification of grassland management over a 45-year period by additions of organic fertilisers largely increased the SOC stocks of the top 20cm of soils in Northern Ireland compared to unfertilised plots. They also showed that the frequency of ploughing and reseeded within a number of working farms did not significantly affect the topsoil (0-20cm) SOC stocks over a 50 year period (Fornara *et al.*, 2020). Liming to maintain soil pH is widely considered to be a requisite for maintaining sward quantity and quality, but agricultural lime comprises calcium carbonate (CaCO_3) which leads to the release of CO_2 . However, these emissions may be partly offset by increased grass production and increasing amounts of organic carbon being stored in the soil. Jones *et al.* (2006) investigated the impact of poultry manure, cattle slurry, sewage sludge, inorganic fertilisers (ammonium nitrate or urea) on C cycling and sequestration in silage production on imperfectly drained noncalcareous gleys. While the organic fertilisers increased losses of CO_2 through soil respiration, SOC contents increased compared to mineral fertilisers but there was also a non-significant increase in SOC stocks in the latter compared to the control plots at least within the upper 10cm. The greatest increases in SOC were in the upper 10cm of the soil in plots treated with sewage pellets and poultry manure. However, the overall GHG balance effectively cancelled out any GHG benefits from C sequestration due to losses of N_2O and CH_4 , which are more prevalent on imperfectly and poorly drained soils (Lilly *et al.*, 2009). Increases in SOC were also reported by Conant *et al.* (2017) when grasslands were fertilised, with greatest increases recorded where organic fertilisers were used and where legumes were part of the grassland species mix. **It is important to note that experimental data show that potential increases in grassland SOC stocks following changes in intensity of grassland management are not linear (Smith, 2014) and that the rate of increase slows with time** to reach a new equilibrium between input of organic matter and its decomposition. The rate of decomposition is determined by the nature of the organic material, the climate and disturbance to the soil (for example, by ploughing).

Conversion from grassland to arable. Much of the intensively managed grassland at Glensaugh is in LCA class 3, division2 which implies the land is also capable of growing arable crops. Potential land use changes could be to a break crop for fodder or to bioenergy cropping, for example. **Although some studies report no change in SOC stocks following land use changes from grassland to arable, particularly at depths >30cm (Li *et al.*, 2020), most report that conversion of grassland to arable land will lead to a loss of SOC.**

Conversion from grassland to woodland. The likely direction of changes in SOC stocks following conversion of grassland to woodland is unclear - some authors have reported a positive change (eg Soussana *et al.*, 2004) while others have reported a loss of SOC (eg, Hannam *et al.*, 2016). A meta analyses of 103

publications from 29 countries by Deng *et al.*, (2016) showed both gains and losses of SOC recorded from different studies. They suggested that the time after land use conversion from grassland to woodland may be a factor in these conflicting results with initial inputs of understory biomass following afforestation increasing SOC until canopy closure, then a decline in understory biomass causing a subsequent SOC decline. SOC was predicted to increase again due to inputs of leaf litter and dead tree roots. Thus, the time of the soil sampling in relation to when the soil was afforested could affect the determination of the direction of change in SOC stock. Indeed, West (2011) suggests initial losses of between 0 and 10% of the carbon in the top 30cm due to site preparation of SOC from mineral soils on afforestation (Table 4) though they suggest that SOC will then begin to accumulate in the following decades to reach a new equilibrium.

Table 4: Proportion of mineral topsoil (0-30cm depth) SOC lost during ground preparation for afforestation (West *et al.*, 2011).

| Planting method | Percentage SOC lost |
|---|---------------------|
| Hand Screening, Hand Turfing and Mounding | 0 |
| Forestry Ploughing (Shallow Turfing) and Scarifying | 2 |
| Forestry Ploughing (Deep Turfing and Tine) | 5 |
| Agricultural Ploughing | 10 |

Conversion of grassland to agroforestry. A number of improved, intensively managed grassland fields at Glensaugh were planted with trees in 1988 at three different densities to investigate the effects of agroforestry systems on livestock production systems. Three tree species (Scots Pine, Larch and Sycamore) were planted at densities of 100, 200, 400 and 2500 trees ha⁻¹, the latter representing commercial woodland densities (Sibbald *et al.*, 2001). The lower density plots of larch have subsequently been removed. A detailed soil survey was undertaken of the Agroforestry plots prior to planting (50m grid spacing plus 10 m transects) but no bulk density measurements were made, so SOC stocks cannot be directly calculated (a retrospective calculation of bulk density is possible via spectroscopy, e.g., see Chapman *et al.*, 2013). Beckert *et al.* (2015) studied changes in SOC at the Glensaugh agroforestry plots 24 years after planting and compared the stocks under the different tree spacings and between tree species. They found that total SOC stocks did not differ between treatments, although stocks within the larch and Scots pine 400m spacing were greater than the stocks under the commercial-spaced woodland plots (2500 trees ha⁻¹). The opposite held for the Sycamore plots. The woodland spacings (2500 trees ha⁻¹) stored more carbon in the labile fractions and the litter layers than the grassland control plots.

Stefano and Jacobsen (2018) and Chatterjee *et al.* (2018) undertook a meta analyses of 250 and 858 conversions of grassland to agroforestry systems respectively, though only a few were relevant to Scottish soil and climatic conditions. Both studies reported overall positive changes in SOC stocks in the top 30cm. Chatterjee *et al.* (2018) reported increased SOC stocks within the first 5 years of establishment of the agroforestry systems in temperate regions. Stefano and Jacobsen found no change in SOC stocks at depths 30-100cm despite the potential for trees to root deeper than grasses.

Although it is possibly unlikely that the climate at Glensaugh would allow the growth of energy crops such as *Miscanthus* (or other crops such as reed canary grass), Holder *et al.*, (2019) found that SOC

declined when grasslands were planted with *Miscanthus*, leading to net GHG losses (including increased emissions of N₂O due to land use change), although these losses were less than conventional energy production from natural gas deposits.

Changes in grassland management to using mob grazing. Rotational mob grazing has been proposed as a means to increase SOC as compared to more traditional continuous grazing systems. The principle behind this grazing method is to divide the land into paddocks which are then grazed in rotation such that the grass is allowed to grow to specified height and dry matter content (kg DM ha⁻¹) before being heavily grazed. When the dry matter content of the paddock reaches a specific level, the livestock are moved on and the grass allowed to regrow (Appendix 2). This grazing method is believed to increase root growth, thereby increasing SOC when the roots die and degrade (Zaralis, 2015). The grass is then grazed at much greater livestock densities than normal but for shorter periods of time before the livestock are moved on to fresh pasture and the most recently grazed grassland area is rested again. To date, there is little scientific literature on the benefits or otherwise of mob grazing. In general, soils that are imperfectly or poorly drained may be at risk of becoming compacted due to the greater density of livestock, with consequences for rainfall infiltration, increased erosion risk and N₂O emissions. The intensively managed grasslands at Glensaugh have a moderate to high topsoil compaction risk (Lilly and Baggaley, 2014; Ball 1985 and 1986) and are moderately to very vulnerable to subsoil compaction (Jones *et al.*, 2003; Lilly and Baggaley, 2018).

Land use changes from extensively managed grassland and moorland

Extensively managed grassland and moorland includes areas classified under IACS as Rough grazing and can include grass-dominated or heather-dominated vegetation communities. Such land covers 570 ha of Glensaugh, plus an additional 197 ha on peat. The non-peat area under rough grazing has mainly podzolic soils (humus-iron and peaty podzols) and can be considered as a moorland. **The fact that these areas are dominated by soils with organic surface layers means that almost any land use change will have a negative impact on the SOC stocks.**

Conversion to intensively managed grassland. The land at Glensaugh that is currently under intensively managed grasslands with humus-iron podzols would have been uncultivated until agricultural improvements occurred (around the 18th Century) and the soils probably would have had an organic surface layer 10-15 cm thick overlying a leached podzolic horizon. Cultivation means that these upper layers become mixed to eventually form a typical agricultural topsoil. Calculation of the current SOC stock to 100 cm depth at Glensaugh for uncultivated humus-iron podzols is 199 t ha⁻¹, while the cultivated humus iron podzols have only 139 t ha⁻¹, demonstrating that cultivation of humus-iron podzols leads to a loss of SOC stock, **thus a conversion from extensively grazed grassland with poor quality grasses and dwarf shrub vegetation to intensively managed grassland results in a loss of SOC.**

Conversion to woodland. There is some conflicting evidence from two recent studies on the change from moorland/rough grazing to woodland. Friggens *et al.* (2020) reported losses or no change in SOC between 12-39 years after tree planting, while Lilly *et al.* (2016) reported increased SOC stocks between 21 and 57 years after the land was afforested in 35 soil profiles, but only due to increased thickness of litter (L) and fermentation (F) layers. These surface layers are quite vulnerable to loss, for

example, during tree harvest. SOC stored deeper within the soil profile is likely to be more stable and would represent a net gain in SOC, however, Lilly *et al.* (2016) found little evidence of increased SOC in deeper soil layers. Friggens *et al.* (2020) showed that the gain in tree biomass C was less than or equal to the loss in the soil between 12-39 years after afforestation. Vanguelova *et al.* (2019) also showed a loss of SOC during the first 30 years after afforestation, though Vanguelova *et al.* (2019) did report that the loss was offset by the carbon associated with litter accumulation after 30 years. As already pointed out, litter layers are fragile and easily lost.

The Woodland Carbon Code (West, 2011) suggests initial losses of SOC from organo-mineral soil on afforestation of between 0 and 40% of the carbon in the top 30cm, depending on ground preparation method (Table 5). Matthews *et al.* (2020) modelled the above ground carbon and below ground carbon (using the ECOSSE model) to identify the role of initial soil conditions and forest management practices on overall net GHG emissions over time. The model simulated losses of SOC during ground preparation of organo-mineral soils prior to simulating changes in SOC over period of tree growth up to 100 years. **Their overall conclusion was that afforesting organo-mineral soils could result in net GHG emissions over decades.**

Table 5: Estimate proportion of organo-mineral topsoil (0-30cm depth) SOC lost during ground preparation for afforestation (source: West, 2011).

| Planting method | Percentage SOC lost |
|---|---------------------|
| Hand Screening | 0 |
| Hand Turfing and Mounding | 5 |
| Forestry Ploughing (Shallow Turfing) and Scarifying | 10 |
| Forestry Ploughing (Deep Turfing and Tine) | 20 |
| Agricultural Ploughing | 40 |

Extensively managed moorlands often include muirburn as a management tool, so we also consider the SOC implications of this component of management. Muirburn is used as a way to regenerate growth of dwarf shrub species as the young shoots are more nutritious than the older shrub. A CxC report (Chapman *et al.*, 2017) concluded that there was insufficient evidence to determine whether muirburn led to a net loss of carbon from the soil. Other losses due to erosion when an organic surface layer was bare after fire were also reviewed by Chapman *et al.* (2017) but they concluded that there was generally little loss prior to the re-establishment of vegetation cover. Chapman *et al.* (2017) also reported little evidence to suggest that the organic surface layer became hydrophobic after burning under normal conditions, so rarely led to increased run-off of rainfall. Hydrophobicity tests on soils from a site of recent burn in Glen Gairn also showed little difference between burnt and unburnt sites (Lilly, pers comm). Brown *et al.* (2014) reported apparent loss of SOC from burnt moorland sites but attributed the loss to dilution of the soil mass by insoluble minerals from the ash.

Land use changes from forestry/woodlands

Woodlands cover around 7% of the current land area at Glensaugh but cover will increase to around 18% under plans for further afforestation. Some of the 1988 agroforestry planting will be thinned, and others may be restocked with an oak dominated mixture.

Felling trees in existing woodland to turn the land into agroforestry was found to have a negative effect on SOC in the upper 30 cm of the soil but a positive effect on SOC over the 0-100 cm depth range overall (Stefano and Jacobson, 2018), although the type of agroforestry system also influenced the amount of the change in SOC.

A meta analyses of 67 sites by Deng *et al.* (2016) and publications by Guo and Gifford (2002) and Murty *et al.* (2002) all reported losses of SOC when forestry was converted to arable land. Soussana *et al.* (2004) reported no change when forestry was converted to grassland contrary to Deng *et al.* (2016) who reported a positive change, though many of these studies were from China and warm and/or arid countries (Deng *et al.* (2016). A meta analyses of 432 C response ratios from 75 sites mainly from temperate forests by Nave *et al.* (2010) showed a general loss of SOC during harvest and that organo-mineral soils were more susceptible to losses than mineral soils, perhaps due to the build-up of relative labile Litter layers in these soils as previously reported (Lilly, *et al.*, 2016; Chapman *et al.*, 2013 and Morison *et al.*, 2012).

Soil type and harvesting method (for example, thinning, stem only or whole tree, and ground preparation for the second rotation) are important in determining carbon impacts of removing trees from an area of land. In their review of forest management on SOC stocks, Mayer, *et al.* (2020) showed that clear-fell generally saw the greatest losses of SOC and these losses were evident in both surface layers and deeper within the soil profile, although SOC stocks start to recover over a period of 10-50 but this recovery period is dependent on soil type, tree species and climate. However, as a normal rotation in the UK for commercial trees is around 40 years, the soil C may not have fully recovered before the next harvest. This shows that growing trees to offset CO₂ emissions may not provide long term C sequestration beyond the first crop rotation. Partial harvesting and leaving enough seed-bearing trees to allow natural regeneration reduces SOC losses compared to clear-fell (Mayer *et al.*, 2020). By not clear-felling, there are still some litter inputs into the soil and the remaining trees provide shade thereby reducing soil temperature and soil respiration, which also reduces SOC losses (Mayer *et al.* 2020). Minimising soil disturbance also helps retain SOC, thus practises like whole tree harvesting (which includes the stump and roots) lead to greater SOC losses than retaining brash and stumps, particularly on organo-mineral soils (Vanguelova *et al.*, 2017).

Other land use changes, e.g. restoration of peatland

There are some small unquantified areas of eroded peat on Thorter Hill. Restoring these areas would increase the SOC stocks of the farm and limit further erosion (e.g. see Artz *et al.*, 2015, Evans *et al.*, 2014).

Estimating net GHG emissions for a farm unit

Several agriculture practices have potential to sequester carbon in soil, but in some cases, they may increase emissions of other GHG gases like CH₄ and N₂O. At Glensaugh, management practices like the application of fertilizer will lead to increase in N₂O emissions which has 298 times more global warming potential than CO₂. At Glensaugh, methane is mainly produced by enteric fermentation of livestock and manure storage activities. Methane has a global warming potential that is 28 times greater than CO₂. Methane emissions are primarily driven by livestock numbers, species/breed and the type of feed they consume. Ruminants like beef and dairy cattle are the principal source of methane emissions producing the most methane per unit of feed consumed. While there are other benefits to increasing SOC, there is a need to take account of the balance between soil carbon sequestration and other GHG emissions to calculate net GHG fluxes. **GHG mitigation measures will need to identify management practices that maintain or sequester carbon in soil and also reduce other GHG emissions.**

Land use land management changes can cause associated changes in GHG emissions and SOC stocks. Each soil type has a carbon carrying capacity and an equilibrium carbon content depending on vegetation and other biophysical characteristics. By using process-based understanding of systems and expert knowledge we are able to show likely directions of net GHG emissions in relation to the plausible land use changes at Glensaugh (Table 6). A more detailed description of potential net GHG emissions is given in Ovando (2020).

Conclusions

Despite extensive literature on the impact on SOC stocks from land use change, there is limited information relevant to the hills and uplands where organic and organo-mineral soils predominate. Studies in Scotland where changes in SOC stocks have been measured over time (e.g. Chapman et al., 2013; Lilly et al., 2016; Beckert et al., 2016; Lilly et al., 2020; Friggens, et al., 2020) give a confusing picture suggesting that further work is needed. The soils and land use at Glensaugh are representative of UK hill farms and, as such, provides an ideal research platform in which to assess the impact of change on SOC stocks due to changing land use. As much of the hill land in the UK has soil with organic surface layers, there is considerable scope for SOC losses and perhaps less scope for net gains. It is also important not to take changes in SOC stocks in isolation but also to consider the effect of land use change on emissions of other GHGs besides CO₂, particularly N₂O through the application of fertilisers (Jones *et al.*, 2006). Within mineral soils, there are additional benefits to increasing or maintaining SOC stocks such as improved water holding capacity and infiltration to increase resistance to both drought and extreme rainfall. However, Smith (2008) pointed to the increased competition for land for alternative uses and simply the desire for land managers to undertake land management practices that are beneficial to the land holding/farm business but do not optimise SOC sequestration.

Future work should include a more detailed and systematic review of the literature that specifically pertains to the soil types found at Glensaugh to be able to determine rates of change rather than simply direction of change. This would allow a more detailed examination of the offset, or otherwise, of biomass production and the overall GHG balance.

Despite there being a substantial number of locations on the farm where the soils have been sampled, for example, the grid survey prior to establishment of agroforestry, ECN (Environmental Change Network) samples and agronomic samples to determine nutrient status, most lack measurements of bulk density necessary to calculate SOC stocks. To set a baseline by which changes in SOC stocks can be measured, a systematic sampling scheme should be implemented as soon as possible to provide the data that is currently lacking. This sampling scheme should encompass all soil types, take samples to measure soil organic carbon concentrations and bulk density, and provide robust estimates of stone content and horizon thickness to allow SOC stocks to be calculated.

Table 6: Likely direction of change of net GHG emissions due to a change in Land use, colour-coded by soil type (see key below table).

| From \ To | Arable/break crop | | | | | | Intensive grazing | | | | | | Extensive grazing | | | | | | Agroforestry | | | | | | Forestry | | | | | | | | | | | |
|-------------------|-------------------|----|---|---|---|---|-------------------|----|---|---|---|---|-------------------|----|---|---|---|---|--------------|----|---|---|---|---|----------|----|---|---|---|---|---|---|---|---|---|---|
| Arable/break crop | - | -- | - | - | - | - | ↖ | ↖ | ↖ | ↖ | ↖ | ↖ | ↖ | ↖ | ↖ | ↖ | ↖ | ↖ | ↖ | ↖ | ↖ | ↖ | ↖ | ↖ | ↖ | ↖ | ↖ | ↖ | ↖ | ↖ | ↖ | ↖ | ↖ | ↖ | ↖ | ↖ |
| Intensive grazing | ↖ | ↖ | ↖ | ↖ | ↖ | ↖ | - | -- | - | - | - | - | ↖ | ↖ | ↖ | ↖ | ↖ | ↖ | ↖ | ↖ | ↖ | ↖ | ↖ | ↖ | ↖ | ↖ | ↖ | ↖ | ↖ | ↖ | ↖ | ↖ | ↖ | ↖ | ↖ | ↖ |
| Extensive grazing | ↖ | ↖ | ↖ | ↖ | ↖ | ↖ | ↖ | ↖ | ↖ | ↖ | ↖ | ↖ | - | -- | - | - | - | - | ↖ | ↖ | ↖ | ↖ | ↖ | ↖ | ↖ | ↖ | ↖ | ↖ | ↖ | ↖ | ↖ | ↖ | ↖ | ↖ | ↖ | ↖ |
| Agroforestry | ↖ | ↖ | ↖ | ↖ | ↖ | ↖ | ↖ | ↖ | ↖ | ↖ | ↖ | ↖ | ↖ | ↖ | ↖ | ↖ | ↖ | ↖ | - | -- | - | - | - | - | ↖ | ↖ | ↖ | ↖ | ↖ | ↖ | ↖ | ↖ | ↖ | ↖ | ↖ | ↖ |
| Forestry | ↖ | ↖ | ↖ | ↖ | ↖ | ↖ | ↖ | ↖ | ↖ | ↖ | ↖ | ↖ | ↖ | ↖ | ↖ | ↖ | ↖ | ↖ | ↖ | ↖ | ↖ | ↖ | ↖ | ↖ | - | -- | - | - | - | - | - | - | - | - | - | - |

Key to IPCC soil categories in Table 6.

| IPCC soil categories | | | | | |
|----------------------|------------------------|----------------------|------------------------------|-------------------|-------------------|
| Wetland (Peat) | Drained wetland (peat) | Organo-mineral soils | Drained organo-mineral soils | Wet mineral soils | Dry mineral soils |
| | | | | | |

- ↖ GHG emissions increase
- ↗ GHG emissions decrease
- ↕ Can be either a source or sink depending on specific management method adopted

References:

- Artz, R., Saunders, M., Yeluripati, J., Chapman, S., Moxley, J., Malcolm, H., and Couwenberg, J. 2015. Implications for longer-term policy and implementation into the AFOLU Inventory of the IPCC 2013 Supplement to the 2006 Guidelines: Wetlands. Policy Brief. 2015. ClimateXChange Scotland.
- Baggaley, N.J.; Poggio, L.; Gimona, A.; Lilly, A. (2016) Comparison of traditional and geostatistical methods to estimate and map the carbon content of Scottish soils. In: Zhang, G.L., Brus, D., Liu, F., Song, X.D. and Lagacherie, P. (eds.). *Digital Soil Mapping Across Paradigms, Scales and Boundaries*. Springer Environmental Science and Engineering. Springer, Singapore, pp103-111.
- Beckert, M.R.; Smith, P.; Lilly, A.; Chapman, S.J., (2016) Soil and tree biomass carbon sequestration potential of silvopastoral and woodland pasture systems in North East Scotland., *Agroforestry Systems*, 90, 371-383.
- Bibby, J.S., Heslop, R.E.F. and Hartnup, R. 1988. *Land Capability for Forestry in Britain*. Soil Survey Monograph. Macaulay Land Use Research Institute. Aberdeen. ISBN 0708404677.
- Brown, L. E., J. Holden, and S. M. Palmer. 2014. Effects of moorland burning on the ecohydrology of river basins. Key findings from the EMBER project. University of Leeds.
- Bradley, R.I., Bell, J.S., Lilly, A., Jordan, C. and Milne, R., 2005. The derivation and use of a UK database for modelling soil carbon fluxes and land use for the national carbon dioxide inventory. *Soil Use and Management*, 21, 363-369.
- Callesen, I., Stupak, I., Georgiadis, P., Johannsen, V. K. and Østergaard, H.S. 2015. Soil carbon stock change in the forests of Denmark between 1990 and 2008. *Geoderma Regional*, 5, 169-180.
- Vesterdal, LarsCarter, M.R. 2005. Long-term tillage effects on cool-season soybean in rotation with barley, soil properties and carbon and nitrogen storage for fine sandy loams in the humid climate of Atlantic Canada. *Soil and Tillage Research*, 81, 109-120.
- Chapman, S.J., Bell, J.S., Campbell, C.D., Hudson, G., Lilly, A., Nolan, A.J., Robertson, A.H.J., Potts, J.M. and Towers, W. 2013. Comparison of soil carbon stocks in Scottish soils between 1978 and 2009. *European Journal of Soil Science*, 64, 455-465.
- Chapman, S.J., Hester, A.J., Irvine, R.J., Pakeman, R.j. 2017. Muirburn peatland and peat soils - an evidence assessment. Report prepared for ClimateXChange. www.climateexchange.org.uk/research/projects/muirburn-peatland-and-peat-soils/
- Chatterjee, N., *et al.* (2018). Changes in soil carbon stocks across the Forest-Agroforest-Agriculture/Pasture continuum in various agroecological regions: A meta-analysis. *Agriculture, Ecosystems & Environment* 266: 55-67.
- Conant, R.T., Paustian, K. and Elliott, E.T. 2001. Grassland management and conversion into grassland: Effects on soil carbon. *Ecological Applications*, 11, 343-355.
- Conant, R.T., Cerri, C.E.P., Osbourne, B.B. and Paustian, K. 2017. Grassland management impacts on soil carbon stocks: a new synthesis. *Ecological Applications*, 27, 662-668.
- De Stefano, A. and M. G. Jacobson (2017). Soil carbon sequestration in agroforestry systems: a meta-analysis. *Agroforestry Systems*.

- Deng, L., *et al.* (2016). Global patterns of the effects of land-use changes on soil carbon stocks. *Global Ecology and Conservation* 5: 127-138.
- Don, A., Scholten, T. & Schulze, E.D. 2009. Conversion of cropland into grassland: Implications for soil organic carbon stocks in two soils with different texture. *Journal of Plant Nutrition and Soil Science-Zeitschrift für Pflanzenernahrung und Bodenkunde*, 172, 53-62.
- Evans, C., Thomson, A., Moxley, J., Buys, G., Artz, R.R.E., Smyth, .-A., Taylor, E., Archer, N., Rawlins, B.. Initial assessment of greenhouse gas emissions and removals associated with managed peatlands in the UK, and the consequences of adopting Wetland Drainage and Rewetting as a reporting activity in the UK Greenhouse Gas Inventory. 2014. Report to the Department of Energy and Climate Change, November 2014.
- Forestry Commission, 2018. National Forest Inventory (NFI) map for Scotland. Spatial dataset. https://data-forestry.opendata.arcgis.com/datasets/b71da2b45dde4d0595b6270a87f67ea9_0/data.
- Fornara, D.A., Steinbeiss, S., McNamara, N.P., Gleixner, G., Oakley, S., Poulton, P.R., Macdonald, A.J. and Bardgett, R.D. 2011. Increases in soil organic carbon sequestration can reduce the global warming potential of long-term liming to permanent grassland. *Global Change Biology*, 17, 1925-1934.
- Freibauer, A., Rounsevell, M.D., Smith, P. and Verhagen, J. 2004. Carbon sequestration in the agricultural soils of Europe. *Geoderma*, 122, 1-23.
- Friggens, N. L., Hester, A. J., Mitchell, R. J., Parker, T. C., Subke, J. A. and Wookey, P. A. 2020. Tree planting in organic soils does not result in net carbon sequestration on decadal timescales. *Global Change Biology*, 26, 5178-5188.
- Guo, L.B. and Gifford, R.M. 2002. Soil carbon stocks and land use change: a meta analysis. *Global Change Biology*, 8, 345-360.
- Grigal, D. F. and W. E. Berguson (1998). Soil carbon changes associated with short-rotation systems. *Biomass and Bioenergy* 14(4): 371-377.
- Hannam, J., Vanguelova, E., Niziolowski, J., Keay, C., 2016. Assessment of soil carbon stocks after afforestation in England and Wales. In, United Kingdom report to Forest Research. The National Soil Resources. Institute, Cranfield.
- Hansen, E. A. (1993). Soil carbon sequestration beneath hybrid poplar plantations in the North Central United States. *Biomass and Bioenergy* 5(6): 431-436.
- Holder, A. J., Clifton-Brown, J., Rowe, R., Robson, P., Elias, D., Dondini, M., McNamara, N. P., Donnison, I. S. and McCalmont, J. P. (2019). Measured and modelled effect of land-use change from temperate grassland to *Miscanthus* on soil carbon stocks after 12 years. *Global Change Biology Bioenergy* 11, 1173-1186.
- Hooker, T.D. and Compton, J.E. 2003. Forest ecosystem carbon and nitrogen accumulation during the first century after agricultural abandonment. *Ecological Applications*, 13, 299-313.
- IPCC 2006. *IPCC Guidelines for National Greenhouse Gas Inventories; Prepared by the National Greenhouse Gas Inventories Programme*. IPCC, Japan.
- Jenkinson, D.S., Hart, P.B.S., Rayner, J.H. and Parry, L.C. 1987. Modelling the turnover of organic matter in long-term experiments at Rothamsted. *Intecol Bull.*, 15, 1-8

- Jones, R.J.A., Spoor, G., Thomasson, A.J., 2003. Vulnerability of subsoils in Europe to compaction: a preliminary analysis. *Soil & Tillage Research* 73 (1–2) 131–143.
- Jones, S.K., Rees, R.M., Kosmas, D. Ball, B.C. and Skiba, U.M. 2006. Carbon sequestration in a temperate grassland; management and climatic controls. *Soil Use and Management*, 22, 132-142.
- Jug, A., Makeschin, F., Rehfuess, K. E., Hofmann-Schielle, C. (1999). Short-rotation plantations of balsam poplars, aspen and willows on former arable land in the Federal Republic of Germany. III. Soil ecological effects. *Forest Ecology and Management* 121(1-2): 85-99.
- Kinchesh, P., Powlson, D.S. and Randall, E.W. 1995. ¹³C NMR studies of organic matter in whole soils: H. A case study of some Rothamsted soils. *European Journal of Soil Science*, 46, 139-146.
- Letten, S., van Orshoven, J., van Wesemael, B., Muys, B, and Perrin, D. (2005) Soil organic carbon changes in landscape units of Belgium between 1960 and 2000 with reference to 1990. *Global Change Biology*, 11 (12):2128-2140
- Li, S., Xu, J., Tang, S., Zhan, Q., Gao, Q., Ren, L., Shao, Q., Chen, L. Du, J., and Hao, B. (2020). A meta-analysis of carbon, nitrogen and phosphorus change in response to conversion of grassland to agricultural land. *Geoderma* 363: 114149.
- Lilly, A & Baggaley, N.J. 2014. Developing simple indicators to assess the role of soils in determining risks to water quality, CREW project number CD2012_42.
- Lilly, A. and Baggaley N.J. 2018. Subsoil compaction risk map of Scotland (partial cover). James Hutton Institute, Aberdeen.
- Lilly A, Baggaley NJ, Edwards AC. 2020. Changes in the carbon concentrations and other soil properties of some Scottish agricultural soils: Evidence from a resampling campaign. *Soil Use and Management*; 36:299–307. <https://doi.org/10.1111/sum.12562>.
- Lilly A.; Ball, B.; McTaggart, I.; DeGroot, J., (2009) Spatial modelling of nitrous oxide emissions at the national scale by upscaling using soil, climate and land use information., *Global Change Biology*, 15, 2321-2332.
- Lilly, A. and Chapman, S.J. 2015. Assessing changes in carbon stocks of Scottish soils: lessons learnt. - - *Earth and Environmental Science*, 25, Article No. 012016. 16.
- Lilly, A.; Chapman, S.J.; Perez-Fernandez, E.; Potts, J., (2016) Changes to C stocks in Scottish soils due to afforestation., Contract Report to Forestry Commission, 33pp.
- Matthews, K.B., Bathgate, S. Wardell-Johnson, D., Miller, D., Fitton, N., Jones, E., Randle, T., Matthews, R., Smith, P. and Perks, M. 2020. Not seeing the carbon for the trees? Why area-based targets for establishing new woodlands can limit or underplay their climate change mitigation benefits. *Land Use Policy* 97 (2020) 104690.
- Mayer, M., Prescott, C. E., Abaker, W. E. A., Augusto, L., Cecillon, L., Ferreira, G. W. D., James, J., Jandl, R., Katzensteiner, K., Laclau, J. P., Laganiere, J., Nouvellon, Y., Pare, D., Stanturf, J. A., Vanguelova, E. I. and Vesterdal, L. 2020. Tamm Review: Influence of forest management activities on soil organic carbon stocks: A knowledge synthesis. *Forest Ecology and Management* 466, 118127.
- Morison, J., Matthews, R., Miller, G., Perks, M.P., Randle, T., Vanguelova, E., White, M. and Yamulki, S. 2012. *Understanding the carbon and greenhouse gas balance of forests in Britain*. Forestry Commission Research Report 18. Forestry Commission, Edinburgh. 1–149pp.

- Moxley, J., Anthony, S., Begum, K., Bhogal, A., Buckingham, S., Christie, P., Datta, A., Dragosits, U., Fitton, N., Higgins, A., Myrgeiotis, V., Kuhnert, M., Laidlaw, S., Malcolm, H., Rees, B., Smith, P., Tomlison, S., Topp, K., Watterson, J., Webb, J., and Yeluripati, J. 2014. Capturing Cropland and Grassland Management Impacts on Soil Carbon in the UK LULUCF Inventory . SP1113. 2014. DEFRA. Final Report of the SP1113 project, prepared for the Department for Environment, Food and Rural Affairs .
- Murty, D., Kirschbaum, M.U., Mcmurtrie, R.E. and MCGilvray, H. 2002. Does conversion of forest to agricultural land change soil carbon and nitrogen? A review of the literature. *Global Change Biology*, **8**, 105-123.
- Nave, L.E., Vance, E.D., Swanston, C.W., Curtis, P.S., 2010. Harvest impacts on soil carbon storage in temperate forests. *For. Ecol. Manage.* 259, 857–866.
- Ovando, P. 2020. Application of the Natural Capital Protocol at Glensaugh Farm. James Hutton Institute. Living Document Version 1. Accessed 21/09/20.
[https://www.hutton.ac.uk/sites/default/files/files/ExcutiveSum1908\(1\).pdf](https://www.hutton.ac.uk/sites/default/files/files/ExcutiveSum1908(1).pdf)
- Ovington, J. D. (1956). Studies of the Development of Woodland Conditions Under Different Trees: IV. The Ignition Loss, Water, Carbon and Nitrogen Content of the Mineral Soil. *The Journal of Ecology* 44(1): 171.
- Poeplau, C., Don, A., Vesterdal, L., Leifeld, J., Van Wesemael, B. A. S., Schumacher, J. and Gensior, A. (2011). Temporal dynamics of soil organic carbon after land-use change in the temperate zone - carbon response functions as a model approach. *Global Change Biology* 17, 2415-2427.
- Poulton, P., Johnston, J., Macdonald, A., White, R. and Powlson, D. (2018). Major limitations to achieving "4 per 1000" increases in soil organic carbon stock in temperate regions: Evidence from long-term experiments at Rothamsted Research, United Kingdom. *Global Change Biology* 24, 2563-2584.
- Robertson, G. P. and P. M. Vitousek (1981). Nitrification Potentials in Primary and Secondary Succession. *Ecology* 62(2): 376-386.
- Sibbald AR, Eason WR, Mcadam JH, Hislop AM (2001) The establishment phase of a silvopastoral national network experiment in the UK. *Agroforestry Systems* 53:39–53.
- Smith, P., Smith, J., Flynn, H., Killham, K., Rangel-Castro, I., Foereid, B., Aitkenhead, M, Chapman, S., Towers, W., Bell, J., Lumsdon, D., Milne, R., Thomson, A., Simmons, I., Skiba, U., Reynolds, B., Evans, C., Frogbrook, Z., Bradley, I., Whitmore, A, and Falloon, P. 2007. ECOSSE - Estimating carbon in organic soils sequestration and emissions. Edinburgh, Scottish Executive Environment and Rural Affairs Department.
- Smith, P. 2008. Land use change and soil organic carbon dynamics. *Nutrient Cycling in Agroecosystems*, 81, 169-178.
- Smith, P. 2014. Do grasslands act as a perpetual sink for carbon? *Global Change Biology*, 20, 2708-2711.
- Smith, P., Powlson, D., Glendinning, M.A.R.G. and Smith, J.O. 1997. Potential for carbon sequestration in European soils: Preliminary estimates for five scenarios using results from long-term experiments. *Global Change Biology*, 3, 67-79.
- Soil Survey of Scotland Staff (1970-1987). Soil maps of Scotland (partial coverage) at a scale of 1:25 000. Macaulay Institute for Soil Research, Aberdeen.
- Soil Survey of Scotland Staff (1984-87). Land Capability for Agriculture maps of Scotland at a scale of 1:50 000. Macaulay Institute for Soil Research, Aberdeen.

- Soil Survey of Scotland Staff (1989). Land Capability for Forestry maps of Scotland at a scale of 1:250 000. Macaulay Institute for Soil Research, Aberdeen.
- Soussana, J.F., Saletes, S., Smith, P., Schils, R.L.M., Ogle, S., Amèzquita, M.C., Buendia, L., Ewert, F., Hensen, A. and Kuikman, P.J. 2004. Greenhouse gas emissions from European grasslands. *Specific Study*, 3.
- Tang, S., Guo, J., Li, S., Li, J., Xie, S., Zhai, Xiajie., Wang, C., Zhang, Y. and Wang, K. (2019). Synthesis of soil carbon losses in response to conversion of grassland to agriculture land. *Soil and Tillage Research* 185: 29-35.
- Vanguelova E.I., Crow, P., Benham, S., Pitman, R., Forster, J., Eaton, E.L., Morison, J.I.L. 2019. Impact of Sitka spruce afforestation on the carbon stocks of peaty gley soils - a chronosequence study in the north of England. *Forestry*. 92, 242-252.
- Vanguelova, E.I., Pitman, R., Benham, S., Perks, M., Morison, J.I., 2017. Impact of Tree Stump Harvesting on Soil Carbon and Nutrients and Second Rotation Tree Growth in Mid-Wales, UK. *Open Journal of Forestry* 7, 58–78.
- Vesterdal, L., Ritter, E. and Gundersen, P. 2002. Change in soil organic carbon following afforestation of former arable land. *Forest Ecology and Management*, 169, 137-147.
- Vleeshouwers, L.M. and Verhagen, A. 2002. Carbon emission and sequestration by agricultural land use: a model study for Europe. *Global Change Biology*, 8, 519-530.
- West, V. 2011. Soil Carbon and the Woodland Carbon Code. *Forest Research*.
- Zak, D.D., Grigal, D.F., Gleeson, S and Tilman, D. 1990. Carbon and nitrogen cycling during old-field succession - constraints on plant and microbial biomass. *Biogeochemistry*, 11, 111-1.
- Zaralis, K. 2015. SOLID participatory research from UK: Mob Grazing for Dairy Farm Productivity. Sustainable Organic and Low Input Dairying (SOLID). The Organic Research Centre. SOLID Project (Agreement no. 266367 (<http://www.solidairy.eu/>)).

Appendix 1: SOC stocks at Glensaugh by depth.

Table A1: Current estimated total soil organic carbon stock to 15 cm (t)

| Soils | Intensive grazing/break crop | Extensive grazing | Agroforestry | Forestry |
|---------------------------|------------------------------|-------------------|--------------|----------|
| Peat | - | 18,580 | - | - |
| Peaty gleys | - | 2,313 | - | - |
| Peaty gleyed podzols | 3,966 | 21,922 | - | - |
| Humus iron podzols (uc) | - | 21,624 | - | 1,651 |
| Humus iron podzols (c) | 1,920 | - | 97 | - |
| Noncalcareous gleys | 655 | 293 | - | 107 |
| Brown earths | 2 | 277 | 1,031 | 54 |
| Brown earths with gleying | 1,999 | 739 | - | 174 |
| Alluvial soils | 275 | 3,233 | 64 | 358 |

(uc) = uncultivated; (c) =cultivated; - combination does not occur

Table A2: Current estimated area weighted soil organic carbon stock to 15 cm (t C ha⁻¹)

| Soils | Intensive grazing/break crop | Extensive grazing | Agroforestry | Forestry |
|---------------------------|------------------------------|-------------------|--------------|----------|
| Peat | - | 94 | - | - |
| Peaty gleys | - | 102 | - | - |
| Peaty gleyed podzols | 93 | 99 | - | - |
| Humus iron podzols (uc) | - | 89 | - | 89 |
| Humus iron podzols (c) | 50 | - | 69 | - |
| Noncalcareous gleys | 54 | 70 | - | 70 |
| Brown earths | 59 | 73 | 59 | 73 |
| Brown earths with gleying | 57 | 63 | - | 63 |
| Alluvial soils | 80 | 102 | 80 | 102 |

(uc) = uncultivated; (c) =cultivated; - combination does not occur

Table A3: Current estimated total soil organic carbon stock to 30 cm (t)

| Soils | Intensive grazing/break crop | Extensive grazing | Agroforestry | Forestry |
|---------------------------|------------------------------|-------------------|--------------|----------|
| Peat | - | 37,160 | - | - |
| Peaty gleys | - | 4,627 | - | - |
| Peaty gleyed podzols | 6,649 | 36,170 | - | - |
| Humus iron podzols (uc) | - | 31,652 | - | 2,482 |
| Humus iron podzols (c) | 3,459 | - | 172 | - |
| Noncalcareous gleys | 1,309 | 587 | - | 214 |
| Brown earths | 4 | 494 | 1,869 | 96 |
| Brown earths with gleying | 3,783 | 1,293 | - | 304 |
| Alluvial soils | 551 | 6,142 | 118 | 664 |

(uc) = uncultivated; (c) =cultivated; - combination does not occur

Table A4: Current estimated area weighted soil organic carbon stock to 30 cm (t C ha⁻¹)

| Soils | Intensive grazing/break crop | Extensive grazing | Agroforestry | Forestry |
|---------------------------|------------------------------|-------------------|--------------|----------|
| Peat | - | 188 | - | - |
| Peaty gleys | - | 205 | - | - |
| Peaty gleyed podzols | 155 | 163 | - | - |
| Humus iron podzols (uc) | - | 130 | - | 134 |
| Humus iron podzols (c) | 90 | - | 123 | - |
| Noncalcareous gleys | 109 | 140 | - | 140 |
| Brown earths | 107 | 131 | 107 | 131 |
| Brown earths with gleying | 108 | 111 | | 111 |
| Alluvial soils | 151 | 191 | 151 | 191 |

(uc) = uncultivated; (c) =cultivated; - combination does not occur

Table A5: Current estimated total soil organic carbon stock to 100 cm (t)

| Soils | Intensive grazing/break crop | Extensive grazing | Agroforestry | Forestry |
|---------------------------|------------------------------|-------------------|--------------|----------|
| Peat | - | 121,536 | - | - |
| Peaty gleys | - | 6,188 | - | - |
| Peaty gleyed podzols | 10,213 | 49,880 | - | - |
| Humus iron podzols (uc) | - | 48,380 | - | 3,821 |
| Humus iron podzols (c) | 5,338 | - | 223 | - |
| Noncalcareous gleys | 1,725 | 756 | - | 276 |
| Brown earths | 6 | 710 | 2,437 | 137 |
| Brown earths with gleying | 4,532 | 1,734 | | 407 |
| Alluvial soils | 945 | 11,036 | 202 | 1,270 |

(uc) = uncultivated; (c) =cultivated; - combination does not occur

Table A6: Current estimated area weighted soil organic carbon stock to 100 cm (t C ha⁻¹)

| Soils | Intensive grazing/break crop | Extensive grazing | Agroforestry | Forestry |
|---------------------------|------------------------------|-------------------|--------------|----------|
| Peat | - | 616 | - | - |
| Peaty gleys | - | 273 | - | - |
| Peaty gleyed podzols | 239 | 225 | - | - |
| Humus iron podzols (uc) | - | 199 | - | 206 |
| Humus iron podzols (c) | 139 | - | 160 | - |
| Noncalcareous gleys | 143 | 181 | - | 181 |
| Brown earths | 140 | 188 | 140 | 188 |
| Brown earths with gleying | 129 | 149 | | 149 |
| Alluvial soils | 257 | 354 | 257 | 354 |

(uc) = uncultivated; (c) =cultivated; - combination does not occur

Appendix 2: Rotational mob grazing regime at Glensaugh

Rotational mob grazing has been practised at Glensaugh on the productive grass leys since 2017. Fields were subdivided into paddocks of between 1.6 ha and 3 ha and ‘mobs’ of up to 250 ewes (or 500 lambs) are grazed round the paddocks in rotation. Livestock are moved into a paddock when the indicative dry matter (DM) measurement reaches 3,000 kg DM ha⁻¹, generally after a rest period of around three weeks (depending on seasonal growth factors). The animals graze the paddock down to 2,400 – 2,500 kg DM ha⁻¹ over a period of 3 to 4 days (depending on mob size, appetite and grass digestibility) before being moved to another paddock. After grazing, nutrients can be applied (for example, in summer FYM is spread at a rate of around 5 t ha⁻¹) and the grass is rested and allowed to regrow. The Glensaugh grazing paddocks are located on a variety of different soil types with the swards on free draining brown earths (e.g. Fungarth series) being typically more productive and less prone to seasonal waterlogging than those on imperfectly drained noncalcareous gleys (e.g. Anniegathel series). However, the latter perform well in dry summers.

Appendix 3: Direction of change in SOC stocks by land use.

| Land Use change | Description | Direction of change | Reference | Notes |
|--|---|---------------------|---|--|
| Arable | | | | |
| Arable to ley/arable rotation | | + | Smith <i>et al.</i> , 1997 | |
| Arable to grassland | Meta analyses of 332 data points from 64 publications | + | Conant <i>et al.</i> , 2017 | |
| Cropland to grassland | Conversion of cropland to grassland (Reshaped the SOC distribution) | \ | Don <i>et al.</i> , 2009 | |
| Cropland to grassland | Long term agricultural use compared to permanent grassland | - | Del Galdo <i>et al.</i> , 2003 | |
| Cropland to grassland | SOC changes in landscape units of Belgium between 1960 and 2000 | + | Lettens <i>et al.</i> , 2005 | |
| Arable to grassland (50 years) | | + | IPCC, 2000 | |
| Cropland to grassland (n=57) | Meta analyses of 103 publications, 160 sites from 29 countries | + | Deng <i>et al.</i> , 2016 | Most of the data from China and warm/arid countries |
| Arable to grassland (35 years) | | + | Jenkinson <i>et al.</i> , 1987 | |
| Arable to grassland (15-25 years) | | + | Vleeshouwers and Verhagen 2002; Guo and Gifford, 2002; Murty <i>et al.</i> , 2002 | |
| Arable to grassland short ley (20 years) | | + | Soussana <i>et al.</i> , 2004 | |
| Arable to permanent pasture | | + | Post and Kwon, 2000 | |
| Arable to agroforestry (0-30cm) | Meta analyses of 250 agroforestry systems | + | Stefano and Jacobsen, 2018; Chatterjee <i>et al.</i> , 2018 | Analyses depend on which type of agroforestry – with crops or not. |
| Arable to agroforestry (0-100cm) | Meta analyses of 250 agroforestry systems | + - | Stefano and Jacobsen, 2018 | |

| Land Use change | Description | Direction of change | Reference | Notes |
|----------------------------------|--|---------------------|---|--|
| Arable to Woodland | Reversion to deciduous woodland | + | Kinchesh <i>et al.</i> , 1995 | |
| Cropland to forest (n=31) | Meta analyses of 103 publications, 160 sites from 29 countries | + | Deng <i>et al.</i> , 2016 | Most of the data from China and warm/arid countries |
| Arable to forestry (115 years) | | + | Hooker and Compton, 2003 | |
| Arable to forestry | | + | Smith <i>et al.</i> , 2007 | |
| Arable to forestry (25 years) | | + | Guo and Gifford 2002; Murty <i>et al.</i> , 2002 | |
| Arable to oak woodland | Denmark | - | Vesterdal <i>et al.</i> , 2002 | |
| Arable to Short rotation coppice | Poplar | + | Hansen,1993 | |
| Arable to Short rotation coppice | Poplar, Willow, Aspen | +/- | Grigal and Berguson, 1998; Jug <i>et al.</i> , 1999 | |
| Cropland to mixed woodland | SOC changes in landscape units of Belgium between 1960 and 2000 | + | Lettens <i>et al.</i> , 2005 | |
| Cropland to broadleaf woodland | | + | Lettens <i>et al.</i> , 2005; Zak <i>et al.</i> , 1990; Robertson and Vitousek, 1981; Poulton, 1996; Poulton <i>et al.</i> , 2018 | Two sites at Rothamsted had not reached equilibrium after >100years (Poulton <i>et al.</i> (2018). |
| Cropland to coniferous woodland | SOC changes in landscape units of Belgium between 1960 and 2000 | + | Lettens <i>et al.</i> , 2005 | |
| GRASSLAND | | | | |
| Grassland to Cropland | Conversion of grassland to cultivated cropland in uppermost 20cm | - | Spohn and Giani, 2011 | |
| Grassland to arable | Meta analyses of 81 sites 0-30cm | - | Tang <i>et al.</i> , 2019 | SOC rate of change slowed after 20 years |
| Grassland to arable | Meta analyses of 81 sites 30-60cm | No change | Tang <i>et al.</i> , 2019 | |
| Permanent crops to arable | | - | Smith <i>et al.</i> , 1997; Guo and Gifford, 2002; Murty <i>et al.</i> , 2002 | |
| Grassland to arable (20 years) | | - | Soussana <i>et al.</i> ,2004 | |

| Land Use change | Description | Direction of change | Reference | Notes |
|--|---|---------------------|---|---|
| Grassland to arable | | - | Smith <i>et al.</i> , 1997; Guo and Gifford, 2002; Murty <i>et al.</i> , 2002 | |
| Grassland to arable 0-30cm | Meta analyses of 92 studies. | - | Li <i>et al.</i> , 2020 | Decrease became greater over time (up to 50 years) |
| Grassland to arable >30cm | Meta analyses of 92 studies | +/- | Li <i>et al.</i> , 2020 | |
| Grassland to arable | Meta analyses of 103 publications, 160 sites from 29 countries | - | Deng <i>et al.</i> , 2016 | Most of the data from China and warm/arid countries (n=27) |
| Grassland intensification | In top 20cm when comparing unfertilised plots with highly fertilised plots over 45 years | + | Fornara <i>et al.</i> , 2020 | |
| Grassland intensification | In top 20cm response to pig and cattle slurry and inorganic NPK varied but general increase | +/- | Fornara <i>et al.</i> , 2020 | |
| Grassland to agroforestry (0-30cm) | Meta analyses of 250 and 858 agroforestry systems | + | Stefano and Jacobsen, 2018; Chatterjee <i>et al.</i> , 2018 | |
| Grassland to agroforestry (0-100cm) | Meta analyses of 250 agroforestry systems | No change | Stefano and Jacobsen, 2018 | |
| Grassland to afforestation (general, 90 years) | | + | Soussana <i>et al.</i> , 2004 | |
| Grassland to Woodland | After 20years of afforestation compared to grassland | + | Del Galdo <i>et al.</i> , 2003 | |
| Grassland to forestry | Meta analyses of 103 publications, 160 sites from 29 countries | +/- | Deng <i>et al.</i> , 2016; Poeplau <i>et al.</i> , 2011 | Most of the data from China and warm/arid countries (n=124) |
| Grassland to forestry | | - | Hannam <i>et al.</i> , 2016 | |
| Grassland to bioenergy crop (Miscanthus) | Miscanthus may not grow at Glensaugh | - | Holder <i>et al.</i> , 2019 | Net GHG loss but less than using Natural gas |
| Extensive grazing/Moorland | | | | |
| Heathland to Hardwood | | + | Ovington, 1956 | |
| Moorland to grassland | | - | Soussana <i>et al.</i> , 2004; Conant <i>et al.</i> , 2001 | |

| Land Use change | Description | Direction of change | Reference | Notes |
|------------------------------------|--|---------------------|---|--|
| Moorland to commercial forestry | Repeat sampling after 21 to 50 years (mean 37) | + | Lilly <i>et al.</i> , 2016 | |
| Moorland to forestry | | - | Friggens <i>et al.</i> , 2020 | MOORCO |
| Moorland to forestry | | - | Vanguelova <i>et al.</i> , 2019 | Loss after 30 but then litter accumulation offset loss. Litter more liable to loss than amorphous peat |
| Muirburn | Loss recorded up to 20cm deep | - | Brown <i>et al.</i> , 2014 | Loss of C concentration attributed to increase in ash content |
| | | | | |
| Forestry | | | | |
| Afforested vs Permanent woodland | Afforested plots compared to permanent forest soils | - | Spohn and Giani, 2011 | |
| Forestry to arable | | - | Guo and Gifford, 2002; Murty <i>et al.</i> , 2002 | |
| Forestry to arable (n=67) | Meta analyses of 103 publications, 160 sites from 29 countries | - | Deng <i>et al.</i> , 2016 | Most of the data from China and warm/arid countries |
| Forestry to grassland | | \ | Soussana <i>et al.</i> , 2004 | |
| Forestry to grassland (n=67) | Meta analyses of 103 publications, 160 sites from 29 countries | + | Deng <i>et al.</i> , 2016 | Most of the data from China and warm/arid countries |
| Forestry to agroforestry (0-30cm) | Meta analyses of 250 and 858 agroforestry systems | -/+ | Stefano and Jacobsen, 2018; Chatterjee <i>et al.</i> , 2018 | |
| Forestry to agroforestry (0-100cm) | Meta analyses of 250 agroforestry systems | +/- | Stefano and Jacobsen, 2018 | |
| Forestry to forestry (n=51) | Meta analyses of 103 publications, 160 sites from 29 countries | - | Deng <i>et al.</i> , 2016 | Most of the data from China and warm/arid countries |
| Forestry to forestry (0-20cm) | Change over time in Danish forest | +/- | Callesen <i>et al.</i> , 2015 | Soils similar to Glensaugh. Mineral soils gained but Organo-mineral soils lost |
| Forestry to forestry | | + | Ovington, 1956 | |

| Land Use change | Description | Direction of change | Reference | Notes |
|-------------------|--|---------------------|---------------------------|--|
| Forest harvesting | Meta analyses of 432 studies from temperate forests. | - | Nave <i>et al.</i> , 2010 | Organo-mineral soils more susceptible to loss than mineral soils |