Scoping study to identify current soil organic carbon stocks and the potential for increasing carbon sequestration in Scottish soils

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Scoping study to identify current soil organic carbon stocks and the potential for increasing carbon sequestration in Scottish soils

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1 Executive summary

This report sets out to critically evaluate the ability of existing datasets to answer a series of questions regarding the status of organic carbon in Scottish soils; how much is there and where, how it is affected by specific land uses, has it changed over time and what is the potential for Scotland's soils to gain or lose carbon.

Soil organic matter (SOM) is derived from the breakdown of leaf litter, dead roots, plant material and animal waste. If the rate of accumulation is greater than the rate of decomposition, then the amount of SOM in the soil increases. However, when decomposition rates exceed the accumulation rate, then greenhouse gases such as carbon dioxide and methane are released and the amount of soil carbon declines.

Soil organic carbon (SOC) is a component of SOM along with other elements such as nitrogen, phosphorous, potassium and calcium. It is usual to measure SOC and convert the value to SOM using a conversion factor that assumes that SOC comprises around 58% of SOM. Loss on ignition (LoI), where a soil sample is burnt in a furnace, is often used as a surrogate of SOM but the loss on ignition value can vary depending on furnace temperature.

Thirty-seven datasets with organic carbon measurements in Scottish soils have been identified. Many have data on soil organic carbon concentrations, but few have data on the quantity (stock) of soil organic carbon. Few of these datasets were specifically designed to quantify soil organic carbon concentrations, stocks or changes over time.

How much carbon is stored in Scottish soils and where is it?

The total stock of soil organic carbon to 100 cm depth in Scottish soils is estimated to be around 3000 Mt C. However, previous analytical methods may have over-estimated soil organic carbon concentrations.

The distribution of soil organic carbon concentrations and stocks have been mapped with examples shown below. The maps give an overview of where the high and low soil organic carbon contents are. The lowest SOC concentrations and stocks are found mainly in the eastern lowlands while the greatest concentrations and stocks are in uplands. Some of these maps can also be viewed online (https://om.hutton.ac.uk/) where they can be queried in more detail, however, the maps are produced at fixed scales and zooming-in does not change the resolution of the map.

How much carbon is stored in soils under different land uses (specifically arable, rotational grassland, permanent grassland and upland semi-natural land)?

Evidence from several datasets shows the least soil organic carbon concentrations in cultivated land are in arable land, followed by land under rotational grassland and then land under permanent or long ley pasture. The same soil types occur in each of these three land use categories suggesting that land use is a key driver of the difference but factors that predispose an area to a particular land use may have a role.

Often the land use at the time of sampling is recorded but land management or land use history are rarely recoded in the datasets. Therefore, only in some cases can soil organic carbon contents be related to land use histories such as the length of time since last ploughed or since the last application of organic fertilisers or since sown to grass. Coupling the Integrated Administration and Control System (IACS) land use data with recent soil organic carbon data could help improve our understanding of some of these factors such as the effect on soil organic carbon contents by including grassland in an arable rotation.

A national scale resampling programme in 2007-9 sampled soils at around 180 locations throughout Scotland and showed that upland or semi-natural soils store more soil organic carbon per hectare than lowland soils. Peatlands have the greatest stocks followed by moorland soils, woodland and then semi-natural grasslands.

Land cover	Carbon $t\ ha^{-1}$
Arable	112
Improved grassland	138
Semi-natural grassland	185
Woodland	268
Moorland	291
Peatland/Bog	528

How has Scotland's soil carbon content changed over time?

The national scale resampling programme in 2007-9 sampled soils at around 180 locations that had been sampled between 20 and 30 years previously. The carbon stocks over the top 100cm of soil were calculated at each location were grouped by land cover. The only land cover type to show an increase in soil organic carbon stocks was woodland, while the soils under arable, improved grassland, semi-natural grassland, moorland and bog showed no statistically significant change.

However, the changes observed in soil organic carbon stocks or topsoil concentrations in Scottish soils over time are not straightforward with some datasets showing no change whilst others show a decline in concentration but no statistically significant change in stocks.

While measurements of soil organic matter concentration are useful and relatively straightforward, measuring soil organic carbon stocks over the full thickness of the soil is a more robust method to assess change as this also takes account of potential changes in depth and density as well as concentration.

Few datasets were collected specifically to investigate change in SOC over time, but it is possible that many could be adapted to give rapid, interim measures of change and help establish suitable sampling densities for any potential monitoring schemes if a clear set of protocols could be developed.

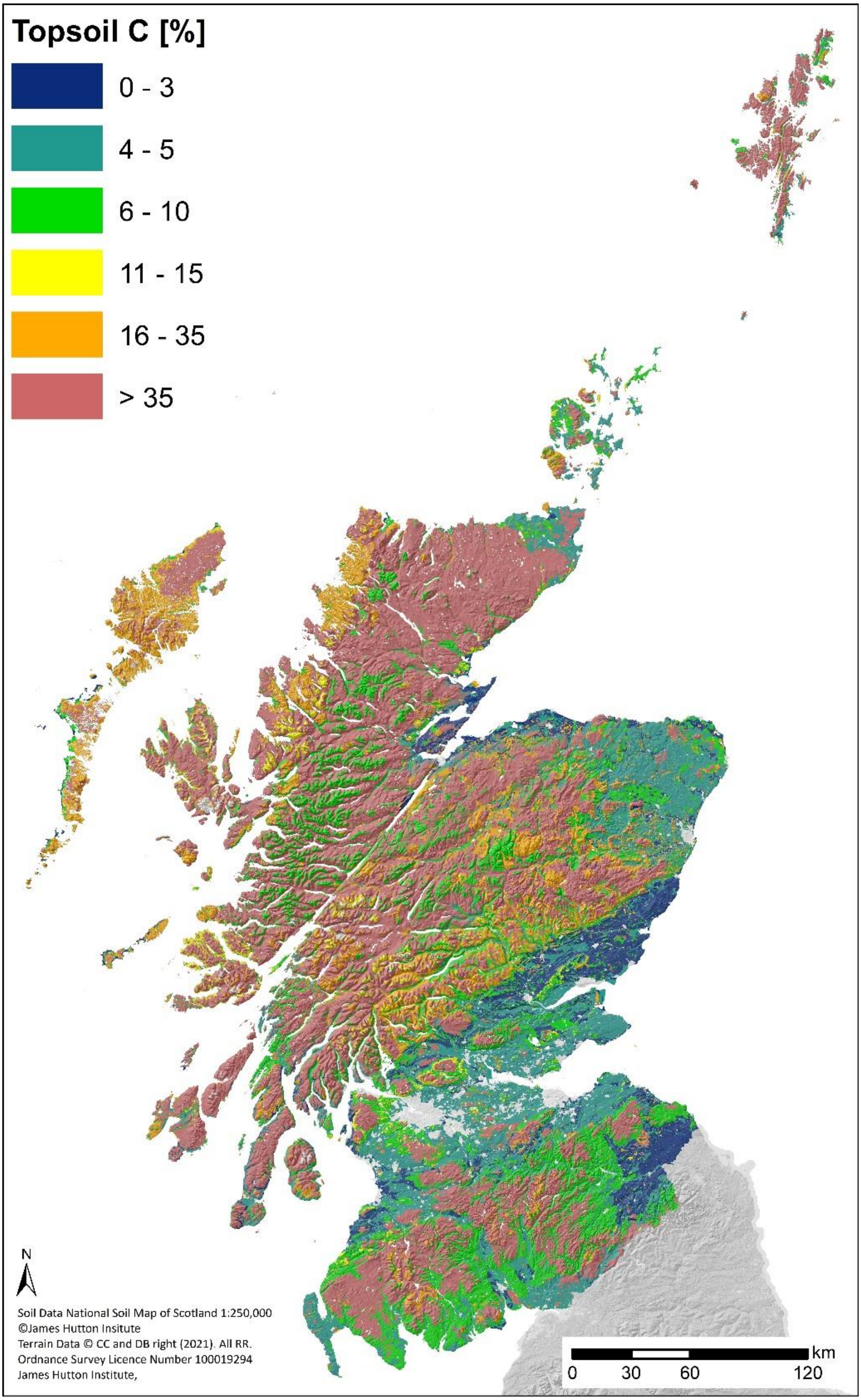
What is the potential for Scotland's soils to gain or lose carbon and what are the likely land use drivers of this change?

It is estimated that there was the potential to store an additional 60 Mt C in Scottish topsoils under grassland soils and 88 Mt C in topsoils under arable land but there was also the risk that up to 112 Mt C of stored soils organic carbon could be lost. However, Scottish soils generally have high soil organic carbon contents and, as the annual rate of carbon accumulation declines as concentrations increase, it may be difficult to further increase the carbon content of Scottish soils under current land use practices.

While there is a considerable body of literature quantifying rates of soil organic carbon accumulation, very few are specific to Scottish conditions and only a few for the UK. Suggested management methods to increase SOC include reduced or no tillage, increased residue returns, fertilising and liming, crop rotation, adding organic manures, growing catch crops and changes in grazing intensity; many which are already practiced.

Land use change is one of the main drivers of soil organic carbon losses. Evidence from the scientific literature shows that changes from semi-natural land to improved grassland and from pasture to arable lead to a loss of soil organic carbon. This is supported by various studies that show soil organic carbon stocks or concentrations are lesser in soils under arable land compared to soils under pasture and in soils under pasture compared to those under semi-natural vegetation. There is less evidence available in the literature to assess the effects of land management on soil organic carbon losses.

Increasing soil organic carbon concentration in soils has multi-benefits besides sequestering carbon to offset greenhouse gas emissions. Soil organic carbon promotes and maintains good soil structure, nutrient retention and soil biodiversity. An improved soil structure allows water infiltration reducing runoff and flooding while retaining sufficient water for crop growth.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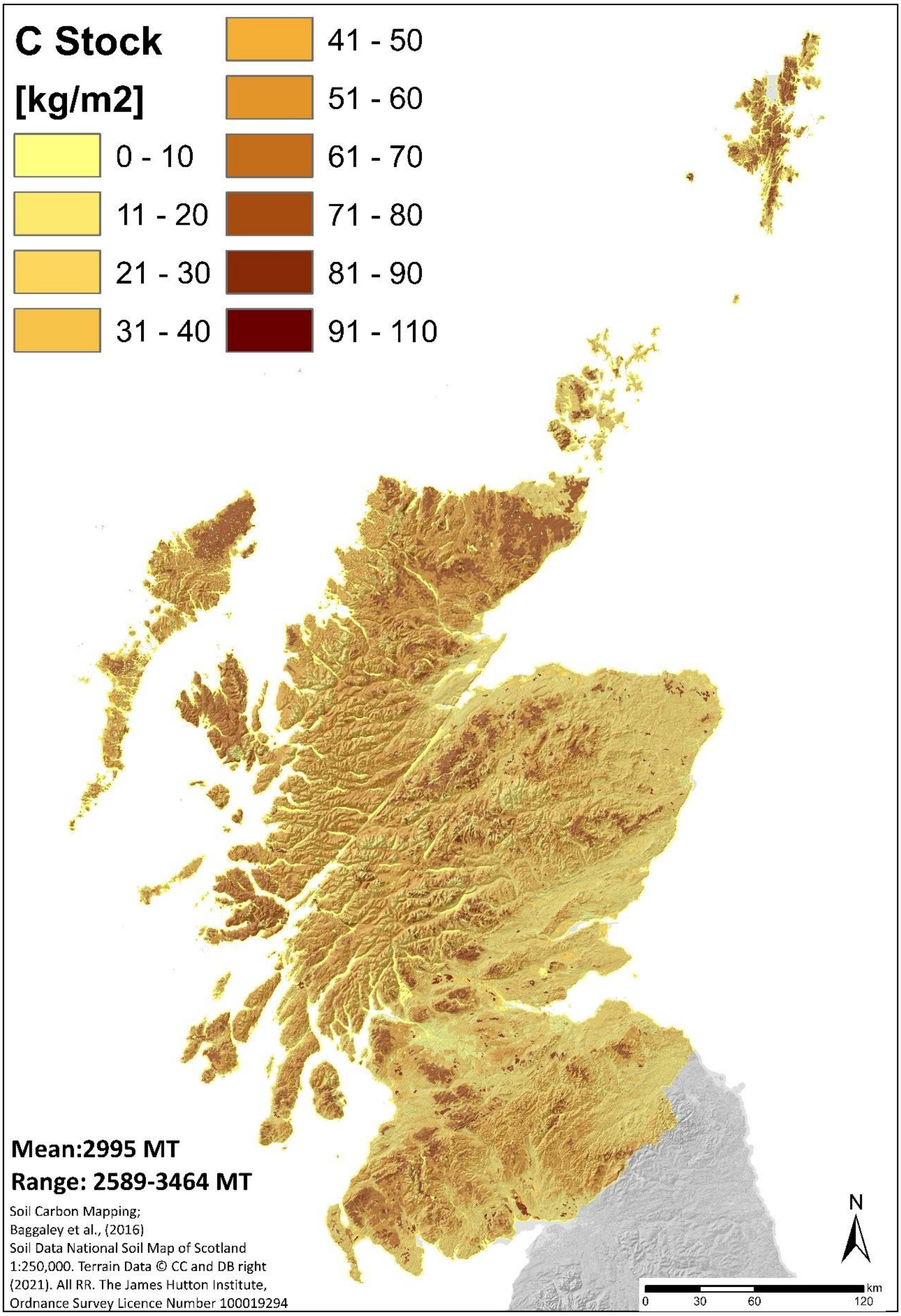

Figure: Topsoil SOC concentrations (top) and Stocks to 100 cm (bottom) based on the National Soil Map of Scotland

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2 Background

Organic matter (or organic carbon) is important in soils in terms of soil fertility, soil biodiversity and reducing the risk of erosion. It promotes and helps to maintain soil structure thereby enabling the infiltration of excess rainfall into the soil while storing sufficient water for crop growth.

Increasingly there is an awareness that soils may be used to sequester (store) carbon as part of the Scottish Government’s targets to achieve net-zero carbon emissions by 2040. The Scottish Government has prioritised actions to improve carbon sequestration in the land use sector within its current Climate Change Plan.

While much of the focus has been on the ability of trees to sequester carbon above-ground, there is also an acknowledgement that cropland and gazing land management can play a part in in reducing atmospheric carbon dioxide (CO_2).

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 the importance of soils but also that soils can both be a sink and a source of CO_2.

Atmospheric CO_2 can be taken up by plants through photosynthesis and converted to organic matter. This organic matter can be deposited into the soil as leaf litter, dead roots, plant material and animal waste. Micro-organisms in the soil decompose this organic matter and, if the rate of accumulation is greater than the rate of decomposition, then the amount of carbon in the soil increases. However, when decomposition rates exceed the accumulation rate, then greenhouse gases such as carbon dioxide and methane are released and the amount of soil carbon declines.

The amount of carbon that can be stored in the soil depends on the type of organic matter, climatic conditions land management practices (both past and present) and, crucially, the amount of carbon already in the soil. The amount of carbon that can accumulate is finite.

This report sets out to critically evaluate the ability of existing datasets, using exemplars, to answer the following questions:

- how much carbon is stored in Scottish soils and where
- how much carbon is stored in soils under different land uses
- how has Scotland’s soil carbon content changed over time
- what is the potential for Scotland’s soils to gain or lose carbon and what are the likely land use drivers of this change.

In addition to answering the above questions, a table of known datasets with soil organic carbon (SOC) data has been compiled (Appendix 1). This table is based on earlier work to review UK-wide soil monitoring datasets (Emmett et al., 2007) and was subsequently modified by Britton (2017) and then by Neilson et al. (2020). Throughout the report, datasets that are in the public domain or easily accessible will be used as examples to show how the data can be used to answer the questions posed. Some of these examples have been slightly updated where appropriate where new data was available. We will also explore how novel Infra-Red spectroscopy can be used to quantify SOC and examine the potential to quantify the role of SOC in water retention, aggregate stability and erosion risk.

3 Terminology used to describe soil organic carbon

Perhaps the simplest measure of soil organic carbon (SOC) or soil organic matter (SOM), is the concentration of carbon in the soil, normally expressed as a percentage (%) or g/kg soil. SOC is most often measured using a dry combustion technique where a soil sample is oxidised at high temperatures and the amount of CO_2 given off it measured. If the soils contain carbonates (eg from limestones or chalks) they are pre-washed in acid to remove this inorganic carbon prior to analysis. The SOC measurement can be converted to SOM using the van Bemmelen factor (1.724) which was proposed in the 1890s and assumes that SOC comprises around 58% of SOM.

SOC is variously reported as percentage SOC, percentage SOM or Loss on Ignition (LoI) though these values are not necessarily interchangeable. Factors such as the furnace temperature can affect measured LoI, and the amounts of other elements (for example, nitrogen, phosphorous, potassium and calcium) within SOM can affect the accuracy of the conversion between SOC and SOM. More recently spectral methods, based on the absorbance patterns of Infra-Red radiation in a soil, have been used to quantify SOC concentrations.

Data shows that SOC concentration of most of Scottish topsoils varies between about 2% and 60% with most mineral topsoils having concentrations <10 % and most organic (peaty) soils having SOC concentrations > 40%. Plotting the frequency of SOC concentrations in surface soil layers using data from the first National Soil Inventory of Scotland (NSIS 1978-88) shows two distinct peaks, one at the lower and one at the higher concentrations. In general, it is useful to consider mineral topsoils as having SOC concentrations <15% and peaty (organic) topsoils as having SOC concentrations >35%. Soils with SOC concentrations between 15 and 35% (organic-mineral) are relatively rare (Figure 1). Note that the mid-range of SOC concentration (organic-mineral) should not be confused with the similar organo-mineral soils which have a peaty layer <50 cm overlying mineral material.

While SOC concentration is a useful indicator, SOC stock (or quantity) is generally considered to be a more robust measurement of SOC as it takes into account the density of the soil and the thickness of the soil layers as well as concentration. This is important as both density and thickness can change through normal cultivation, for example, if heavy machinery is used.

A key example of the importance of measuring stocks comes from the National Soil Inventory of Scotland (2007-9) resampling (Chapman et al, 2013). When SOC concentrations of cultivated soils were compared to the NSIS 1978-88 samples, the concentrations of the topsoils were shown to have declined. However, it was also noticed that the thickness of the topsoils in mineral soils had significantly increased between the two samplings (possibly due to deeper ploughing) leading to no overall change in SOC stocks. In most organic soils, the SOC concentration will only vary slightly as the soils are almost 100% SOM and so change is only really detectable through measuring SOC stock and where changes in the thickness of the layers, for example, by increases from dead plant material or losses through drying and oxidation, are a crucial to the calculation.

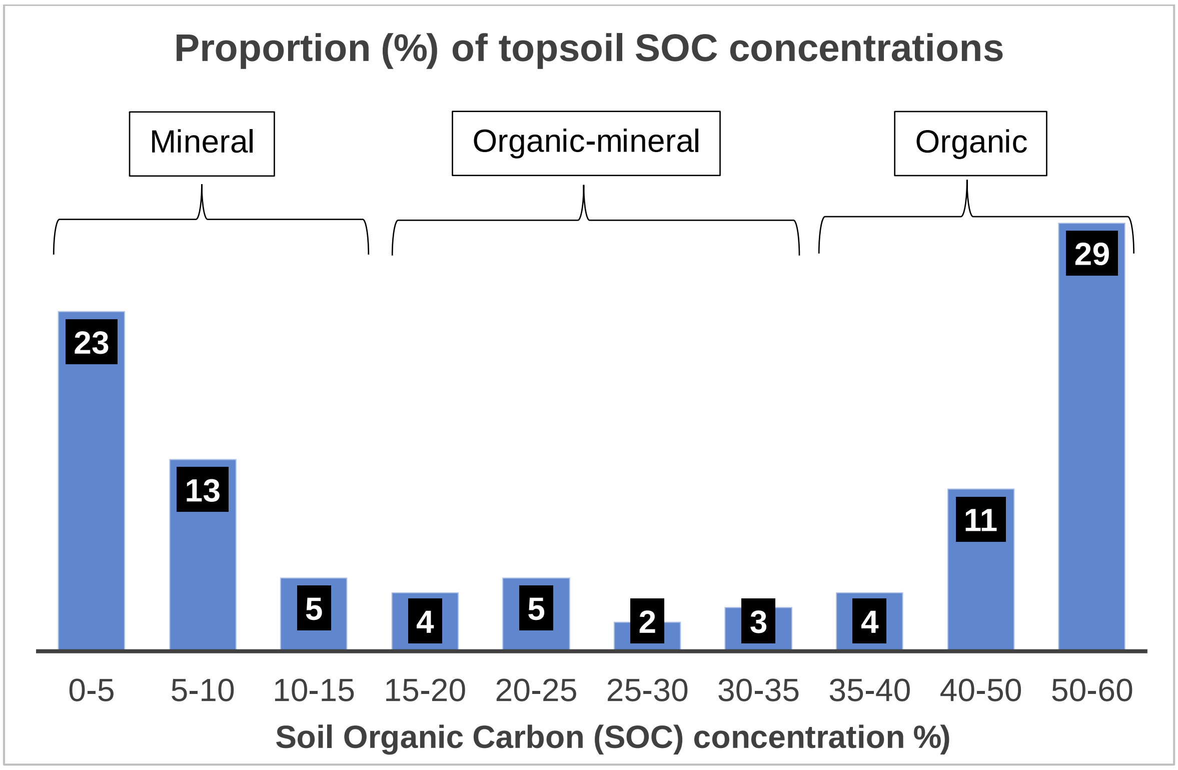

Figure 1: The proportion of topsoils (%) in each SOC class derived from 721 samples from the National Soil Inventory of Scotland 10km grid survey sampled between 1978 and1988.

4 Datasets for Scotland with measurements of soil carbon

Appendix 1 lists some of the datasets that have measurements of SOC in Scottish soils and these will be used throughout to provide examples of the types of data that can be used to answer the questions regarding how much SOC there is and where, has it changed over time and what are the potential for loses or gains. Those datasets marked * in Appendix 1 are component parts of the 'Scottish Soils Database' held by the James Hutton Institute.

A total of 37 datasets have been identified. Some of these datasets (Appendix 1) cover a wide range of soil types and habitats such as the Representative Soil Profile dataset, the National Soil Inventories of Scotland (NSIS), held by the James Hutton Institute and the Countryside Survey (CEH- Centre for Ecology and Hydrology). Other data sets are more restricted to specific land uses, for example, the BioSoil dataset for Woodlands or the Trends in pollution of Scottish Soils for upland habitats.

Appendix 1 also gives information on the extent (National, Regional or Local) of the data and an indication if the soils have been resampled so that change over time can be assessed (for example, NSIS 1978-88 and NSIS 2007-9, Countryside Survey). It also gives information about whether SOC stocks can be calculated, an indication of the depth over which the soils were sampled and the strengths and weaknesses of each dataset. While there are numerous datasets in Scotland where SOC concentrations have been measured there are fewer where SOC stocks have been calculated.

Other data sets that were collected for specific purposes, such as an assessment of aggregate stability or to develop soil health testing (Soilbio) represent specific land use types. These can be used to explore relationships between carbon and other factors such as fertility, erodibility or water retention but also, they hold valuable information on SOC contents for different land uses and land management.

As can be seen from the list of datasets in Appendix 1, Scotland has a wealth of soil data due its long mapping and soil characterisation programme and the long history of soil research, much of it primarily funded by Government.

4.1 Limitations in the datasets

In general terms, datasets that limit the sampling depth to less than the thickness of most topsoils, for example, to 0-15 cm are less useful than those that sample over the full thickness of the soil (for example, to 100 cm) or at least to the full thickness of the topsoil where fixed depth sampling to 15 or 30 cm depth would have resulted in a false result. This is also the case in soils with organic surface layers that comprise almost entirely of organic material, where changes in depth are often the main way that carbon is lost or gained.

A disadvantage in some of the datasets, for example, the Representative Soil Profile database, is the widespread age of the data (from 1940s to present). Changes in analytical methods over time can affect the measured values. Chapman et al. (2013) illustrated this when assessing change over time using the National Soil Inventory data. They found that reported SOC concentrations in the soils sampled in the late 1970s and early 1980s were 11.5% greater when reanalysed. Subsequent analyses of early samples going back to the 1960s, also showed similar differences between old and new analyses. In an internal report, Chapman (2017) suggested multiplying the older SOC concentration data by around 0.9 to align the values with current measurements. Interestingly, Chapman et al. (2013) did not see a similar change in the Loss on Ignition (LoI) values when the soils were reanalysed indicating that the difference was due to changes in methods and/or the instruments used to measure SOC.

The limitations of differences caused by analytical methods or equipment can also be overcome by reanalysing the original sample alongside new samples to ensure consistency in the method. This was the approach taken by Chapman et al. (2013) and by Lilly et al., 2019 and highlights the benefit of archiving sampled soils for future analyses.

5 How much carbon is stored in Scottish soils and where?

Of the datasets listed in Appendix 1, only a few can be used to produce national scale maps of either carbon concentrations or carbon stocks. To do this, these datasets need to have national cover and not be land use specific. One such dataset is the Representative Soil Profiles of Scotland Database held by the James Hutton Institute. This Institute also holds soil spatial (map) data including the National Soil Map of Scotland (Soil Survey of Scotland Staff, 1981) which covers the entire country and the Soil Map of Scotland (partial cover) which covers most of the cultivated land and adjacent uplands (Soil Survey of Scotland Staff, 1970-87).

As both these soil maps show the distribution of the various soil types found in Scotland using the same classification system as used in the Representative Soil Profiles dataset, the soil data can be directly linked to the soil map to show the amount of carbon in Scottish soils and where it occurs.

The Countryside Survey, undertaken by the Centre for Ecology and Hydrology (CEH) in 1978, 1998 and 2007, has also been used to assess how much carbon is stored in Scottish soils and where. Both SOC stocks and SOC concentrations at a depth of 0-15 cm were collected from a number of broad-scale habitats (including arable and horticultural land, improved grassland, various semi-natural grasslands, deciduous woodland, coniferous woodland, heather moorland and peatlands). The concentrations and stocks were then mapped by linking the SOC values with similar habitats in each a 1 km square throughout the country. The maps, therefore, represent carbon stocks and concentrations by habitat types.

5.1 Distribution of soil organic carbon concentrations

Average SOC topsoil concentrations for each of the soil types shown on the National Soil Map of Scotland have been mapped by linking averaged SOC concentrations calculated from the Representative Soil Profiles dataset (with some additional data from the National Soil Inventories, grid and transect samples and some site-specific research samples) to soil map units within a Geographic Information System. The map (Figure 2) of the average topsoil SOC shows the distinctive peaty surface layers of the organo-mineral (soils with an organic surface layer over a mineral subsoil) and peat soils (where the organic surface layer is greater than 50 cm thick) of the hills and uplands as well as lesser SOC concentrations of the mineral soils in the more cultivated lowlands.

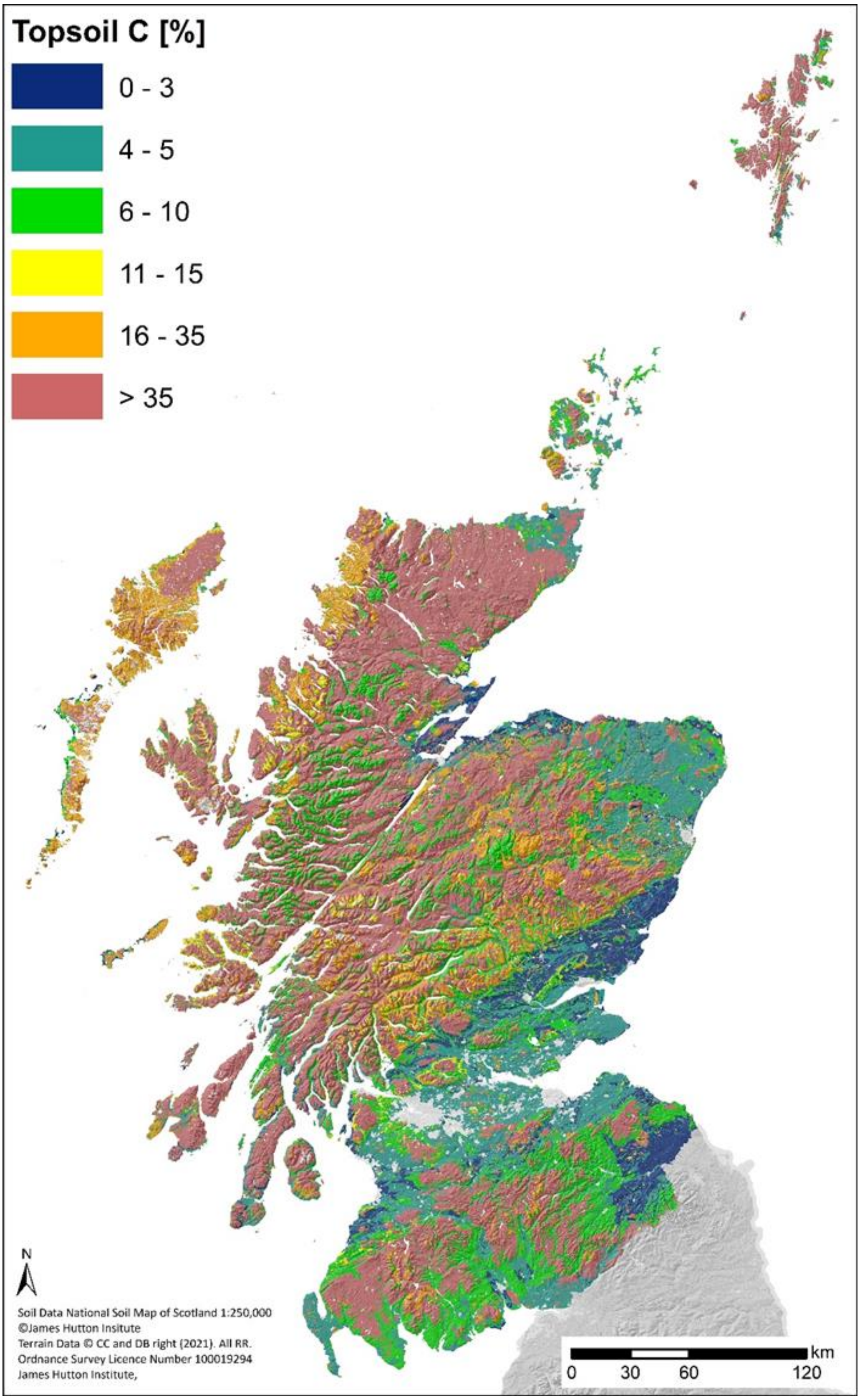

Figure 2: Topsoil SOC concentrations based on the National Soil Map of Scotland and the Representative Soil Profile dataset.

The average carbon concentrations at 0-15 cm for the 2007 Countryside survey were mapped on a 1 km grid using a model-based soil parent material and broad habitat type Figure 3). This map reflects land cover and habitats to a greater extent than the soils underlying them.

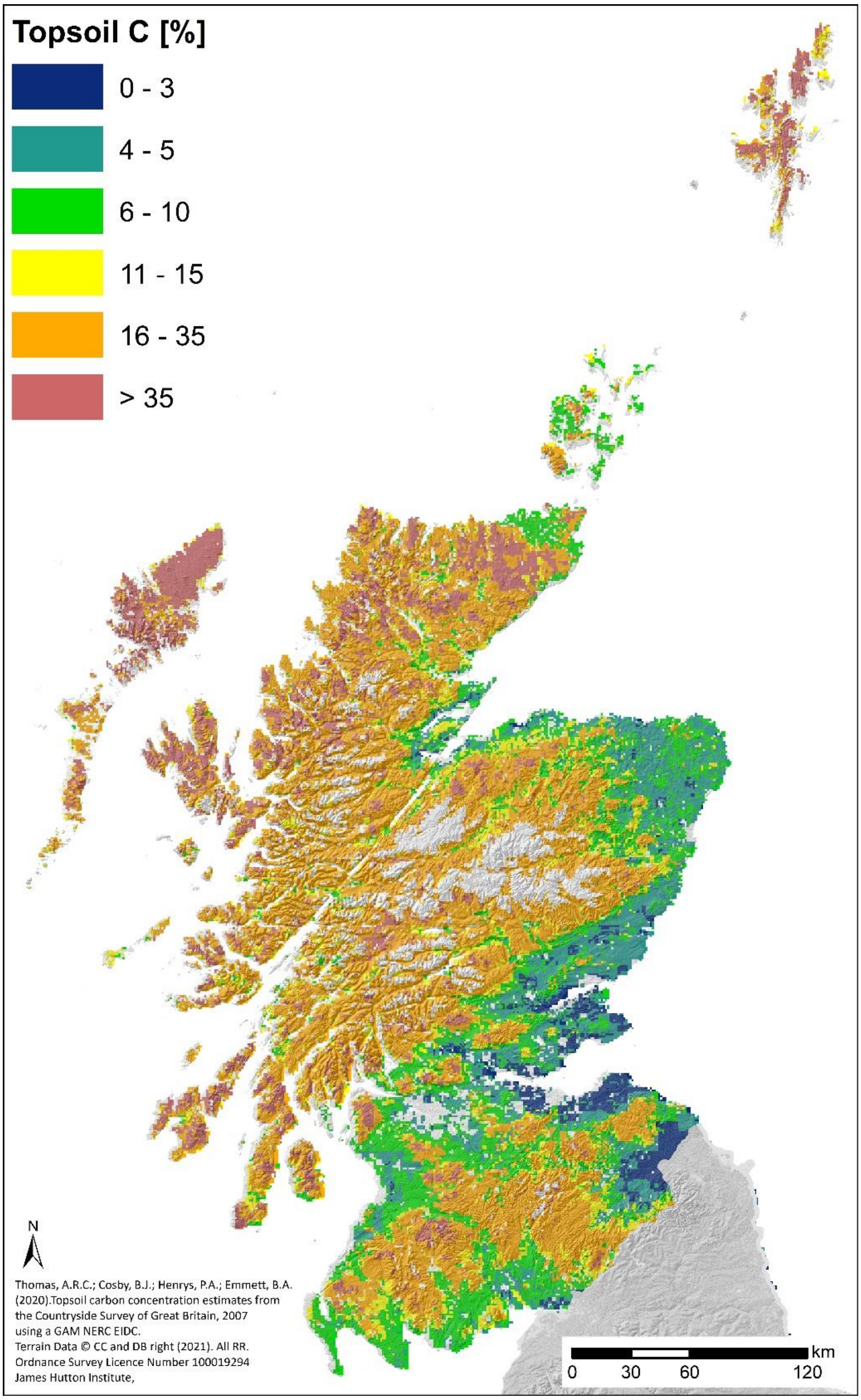

Figure 3: SOC concentrations (0-15 cm) mapped using a statistical model based on habitat and soil forming factors (Countryside Survey, CEH) (Henry et al., 2012).

5.1.1 Limitations in the maps

The National Soil Map of Scotland is based on identifying the soils within specific landforms rather than mapping individual soil types. The number of different soil types within each landform varies from 1 to (in rare and specific cases) 8. This means that in order to map the SOC concentrations, it is generally necessary to select one soil type (generally the most extensive one in the landform unit) to represent the SOC concentration on a map.

This can be overcome with electronic datasets that can be interrogated online (eg Soil Indicators for Scottish Soils (SIfSS) or the Topsoil Organic Matter Tool) where the SOC concentrations of each soil type within the map unit can viewed. As the mapping units on the Soil map of Scotland (partial cover) (Soil Survey of Scotland Staff,1970-1987) mainly comprise only one soil type, the SOC concentrations of each soil type are more easily mapped.
As previously mentioned, some of the data within the Representative Soil Profile database is relatively old and may not be representative of current SOC concentrations but, as already shown, a general correction factor could be applied.

With all national (or regional) scale assessments, it is important to assess the resolution at which the mapping has occurred in order to determine its use in assessing carbon stocks or concentrations across smaller spatial extents. For example, a 1 km gridded data set provides an overview of where highly organic or mineral soils are likely to occur, whereas data based on the partial cover map at 1:25,000 scale could be used to identify areas within a farm that may require specific management, for example areas of peat.

5.2 Distribution of soil organic carbon stocks

There have been many attempts to estimate the quantity of carbon stored in Scottish soils from 1995 where Howard *et al.* estimated the stock of carbon in the upper 100 cm of Scottish soils to be 19,011 Mt C to more recent estimates by Poggio and Gimona (2014), Aitkenhead and Coull (2016, 2020) and Baggaley et al., 2016. These latter estimates coalesce around 3,000 Mt C (Figure 4). Each of the estimates by Poggio and Gimona (2014), Aitkenhead and Coull (2016, 2020) and Baggaley and Lilly used data from the Representative Soil Profile database and/or the National Soil Inventories of Scotland but used different methods to calculate the stocks (Figure 5).

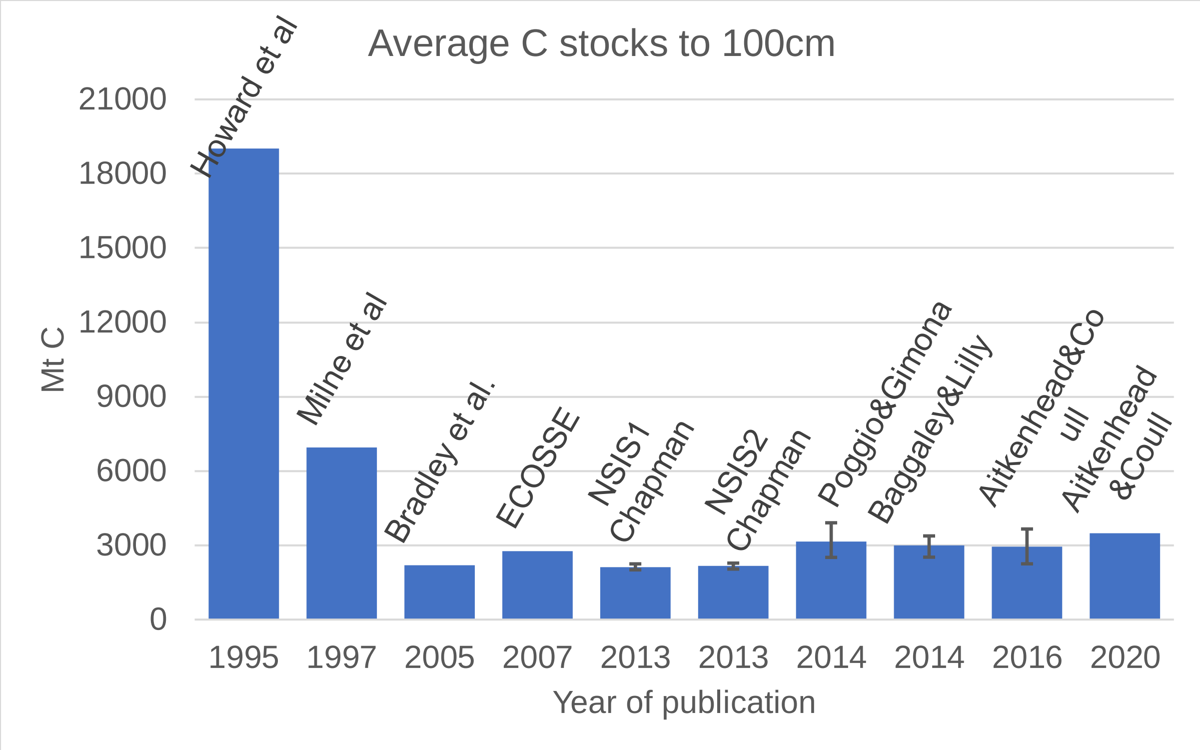

Figure 4: Estimates of SOC stocks in Scottish soils over time with error bars where reported.

Briefly, Baggaley & Lilly (2016) used a method similar to that used to map SOC concentrations (Figure 2). They calculated SOC stocks for each soil type based on average SOC concentration, estimates of typical horizon thicknesses, and predicted bulk density (Figure 5 c). A measure of the uncertainty (shown as error bars in Figure 4) was calculated based on the range in the measured soil carbon and the uncertainty from using a predicted bulk density. The average stock, and associated uncertainty, was then calculated for each soil map unit taking land cover into account and mapped using the National Soil Map combined with a national land cover map.

Poggio & Gimona (2014) and Aitkenhead & Coull (2016,2020) used approaches based on statistical relationships between calculated carbon stocks and different combinations of the key soil forming factors, such as topography, land cover, vegetation information from remote sensing, climate and parent material (Figure 5 a and b). Both methods made use of the National Soil Inventory of Scotland (NSIS 2007-9) data and Poggio & Gimona added measured carbon stocks from 19,500 soil horizons (layers) held within the Scottish Soils Database. While Poggio & Gimona mapped the SOC stocks to 100 cm depth for each 1 km^2 throughout Scotland (excluding Shetland due to the lack of satellite derived land cover data), Aitkenhead & Coull mapped the stocks for each 100 m grid cell.

All these methods have inherent uncertainty as they all rely on models and relationships between various soil properties such as landscape characteristics, but they all give similar values. Appendix 2 outlines where the various statistical uncertainty in the estimates lie.

Maps at this scale or resolution are not suited to managing stocks at a farm level; the Poggio & Gimona map is too crude a resolution, while the Baggaley & Lilly map averages the stocks over the different soil types within the map unit as does Aitkenhead & Coull. Instead, they are designed to give an overview of where the stocks are greatest or least and to give baseline estimates of current national stocks.

Better estimates of SOC stocks could be obtained by improving the resolution of the Poggio & Gimona approach or using maps with a single soil type in each map unit as the basis for the assessment. This is possible with the traditional approach by Baggaley et al. using the more detailed 1:25 000 Soil maps of Scotland (partial cover) which covers around 95% of the cultivated land in Scotland. This approach has been adopted in a project to provide data on topsoil SOC stocks for over 500,000 fields in Scotland, covering 83 % of the total land area and where a correction factor was also applied to the older SOC concentration data.

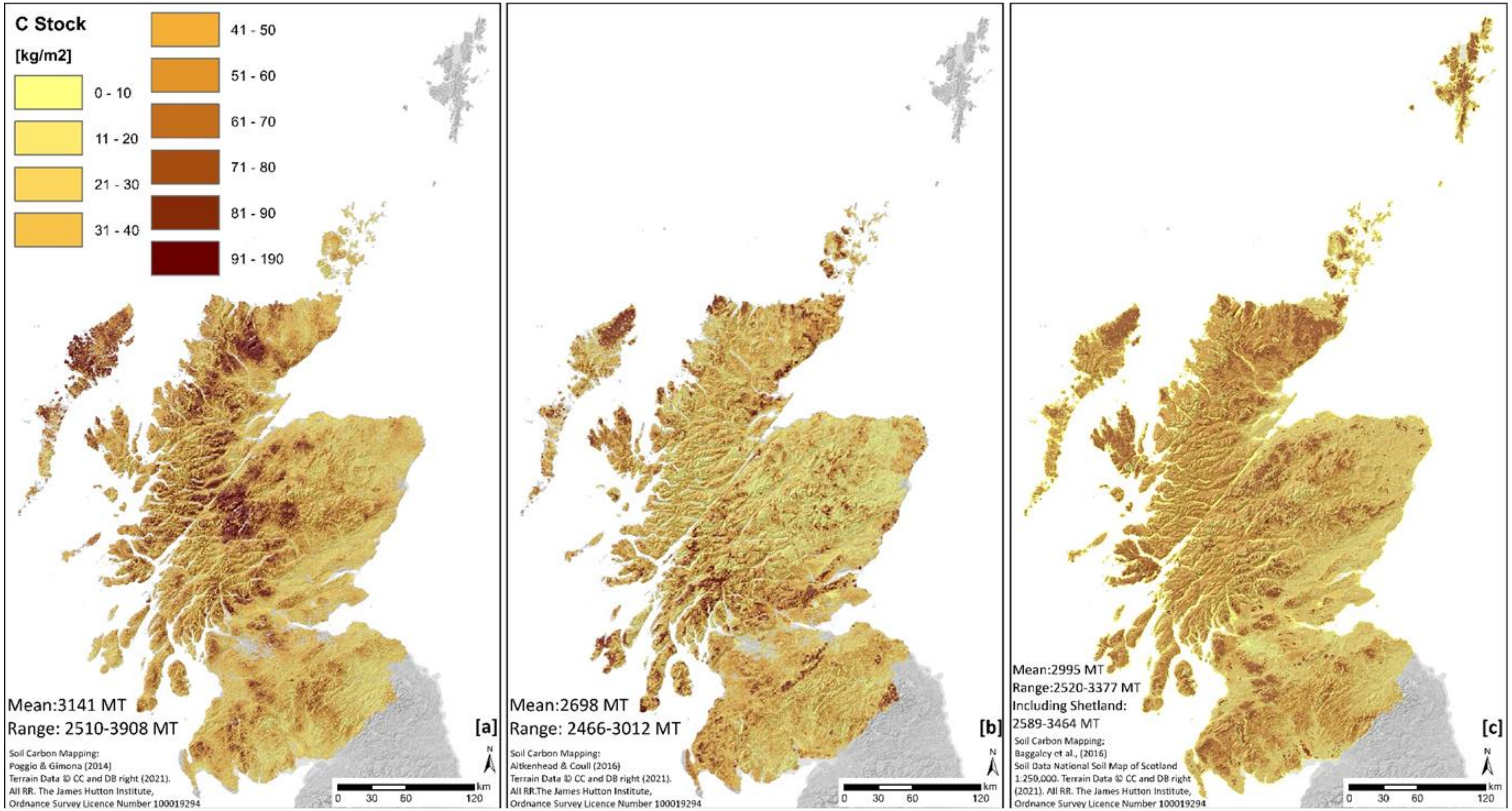

Figure 5: Mapped soil organic carbon stocks to 1 m depth by statistical (a&b) and by traditional mapping (c).

The Stocks to 15cm depth from the combined 1978, 1998 and 2007 Countryside Surveys (Figure 6) have also been mapped on a 1 km grid using a simple statistical method based on characteristics of parent material map and habitat type, providing indication of the spatial distribution of stocks by habitat type (Henrys et al., 2012).

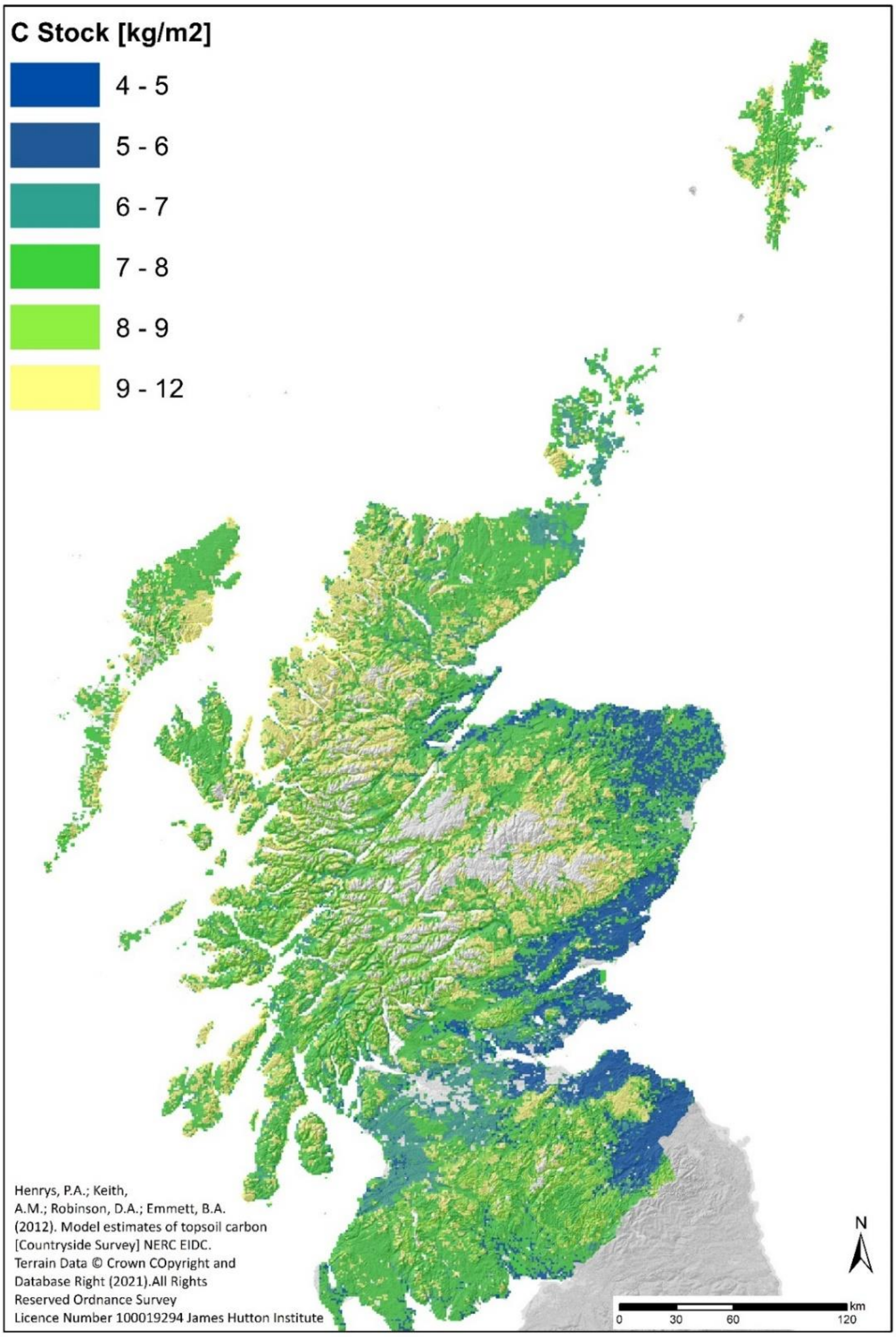

Figure 6: SOC stocks (0-15 cm) from the 2007 Countryside Survey mapped using a statistical model based on habitat and soil forming factors (Henry et al., 2012).

The estimates of the SOC stock in Scottish soils are often calculated to 100cm depth as aligns with the Intergovernmental Panel on Climate Change (IPCC) protocols and, in Scotland, the soil material below this depth generally has little SOC. However, this is not the case for peats which often exceed 100 cm depth. Chapman et al. (2009) estimated that stocks of peat below 100cm could be 500 Mt C.

6 How much carbon is stored in soils under different land uses

Appendix 1 shows the range of existing datasets that have SOC concentrations or stocks, or LoI data and which specific land uses the data represent. In some cases, such as the Representative Soil Profile dataset, the National Soil Inventories or the Countryside Survey, the data are from a number of habitats from lowland arable to montane while others are restricted to one or two land uses.

While some of the soils have been sampled in more recent times, some are either older or cover a long time period, and some are still being added to. All these datasets are useful; the most recent can help establish current SOC concentrations or stocks while the older datasets could be re-sampled to provide estimates of change over time in specific land uses.

6.1 SOC concentrations in relation to land use

The data in the Scottish Soils Database includes a record of the land use at the time the soils were sampled. These data can be used to calculate mean topsoil SOC concentration for soils under arable, rotational or permanent grassland (Table 1). Other datasets with similar SOC concentration data are shown in Table 2 though not all have the capacity to differentiate between these three land uses in the cultivated soils. Although there are data on SOC concentrations in rotational grassland, permanent grassland and arable land, the time since the land changed from arable to rotational grassland or vice versa is not recorded in these data sets. The same soil types occur in each of the three cultivated land use categories suggesting that land use is the main driver of the difference but other factors such as climate that predisposes an area to a particular land use (for example, arable land in eastern Scotland) cannot be wholly ruled out and requires further analyses.

Table 1*:* mean SOC, standard deviation (sd), range within which 90% of the samples occur and sample size of topsoils under arable, rotational grassland and permanent grassland at the time of sampling from the Scottish Soils Database.

Land cover	SOC %				SOM %				Sample number
	Mean	sd	5%ile	95%ile	Mean	sd	5%ile	95%ile	
Arable	3.48	2.03	1.37	7.16	6.0	3.5	2.36	12.34	2992
Rotational grass	4.4	1.98	2.09	7.7	7.59	3.41	3.6	13.27	545
Permanent grass	4.72	2.23	2.22	8.52	8.14	3.84	3.83	14.69	310

Note: no account is taken of the likely differences in measured SOC over time.

The Countryside Survey data measures carbon concentration, and bulk densities, for the top 15 cm of soil, allowing for the calculation of carbon stocks to this depth (Table 2). In 2007 the soils were sampled at 3 to 5 locations within each of 196 1 km grid squares in Scotland. As this survey was initially designed to investigate changes in vegetation, the soil types at the locations were not identified. Therefore, the results can be used to produce average values for broad habitat types (arable and horticultural land, improved grassland, various semi-natural grasslands, deciduous woodland, coniferous woodland, heather moorland and peatlands).

The LUCAS (Land Use and Cover Area frame Survey) dataset from a survey conducted in 2009 and in 2015 has been published by the European Soil Data Centre (JRC, Ispera). The LUCAS sampling frame was designed to survey land use in EU member states and comprised more than 250,000 sample locations. In 2009, the topsoil SOC concentrations was measured at a subset of these locations (around 20,000), 190 sites in Scotland. In 2015, 234 sites were sampled in Scotland (Figure 7) and this dataset also has measured carbon concentrations as well as recorded land cover at each point of which 156 are in arable and improved grasslands (Table 2).

Table 2: mean SOC, standard deviation (sd) and sample size (n) of topsoils under arable or grassland at the time of sampling from various sources.

Source	SOC %			SOM %		
	Date	Mean	sd	Mean	sd	n
LUCAS (Arable)	2015	2.54	0.98	4.38	1.69	52
LUCAS (Temporary grassland)	2015	3.62	1.41	6.24	2.44	4
LUCAS (Grassland)	2015	7.29	7.44	12.57	12.83	100
Countryside Survey (Arable)	2007	3.23	-	5.57	-	-
Countryside Survey (improved grassland)	2007	6.46	-	11.14	-	-
East of Scotland Arable Farms	2007	2.89	0.81	4.98	1.4	27

One way to assess the differences in SOC concentration under arable, rotational grass or permanent and long ley pastures is to make use of the annual Integrated Administration and Control System (IACS) land use data. IACS data contains information on the land use history of the fields and is available digitally from 2000. If positional accuracy of the measurements of carbon is sufficient to confidently place them within a field, then it may be possible to use the land use data in the IACS dataset to determine the sequence of crops and grass to establish the length of time a field has been in pasture or a grass ley with respect to the time the soil sample was taken.

Data sets such as the LUCAS data from 2009 and 2015 and NSIS 2007/2009 and East of Scotland Arable Farms, have sufficient time between the start of the available IACS records and sampling to potentially be able to explore the impact of longer-term management on SOC at a national level. In additional smaller scale surveys, such as the aggregate stability and East of Scotland experimental farms could be added to the analysis (Appendix 1). The Countryside Survey data is only available under licence but if the sample location was known precisely, it could also be used with IACS data to investigate the effect of grassland rotations on changes in SOC. A more thorough analyses of each dataset would be required to assess its usefulness in distinguishing SOC concentrations by land use.

Carbon concentration is a less useful measure in upland soils where the surface layer is often organic. As seen in Figure 2, the SOC concentration of many of these layers are > 50% which is roughly 86 % SOM. The more useful measure is SOC stocks as this takes into account the thickness of the horizon and the density of the soil. Losses or gains in SOC stocks in these soils is often through the accumulation or soil of the thickness of these surface organic layers.

There are a number of additional regional or local datasets that are specific to one land use that could be investigated to provide additional information on the SOC concentrations of Scottish soils. While some of these form part of the Scottish Soils Database (for example, the Farm Grid and Soil map unit transect studies) along with the National Soil Inventories and Representative Soil Profile dataset and are readily accessible, others, for example, the data held by SRUC/SAC in the Scottish Soil Fertility database could be investigated if issues around confidentiality were overcome.

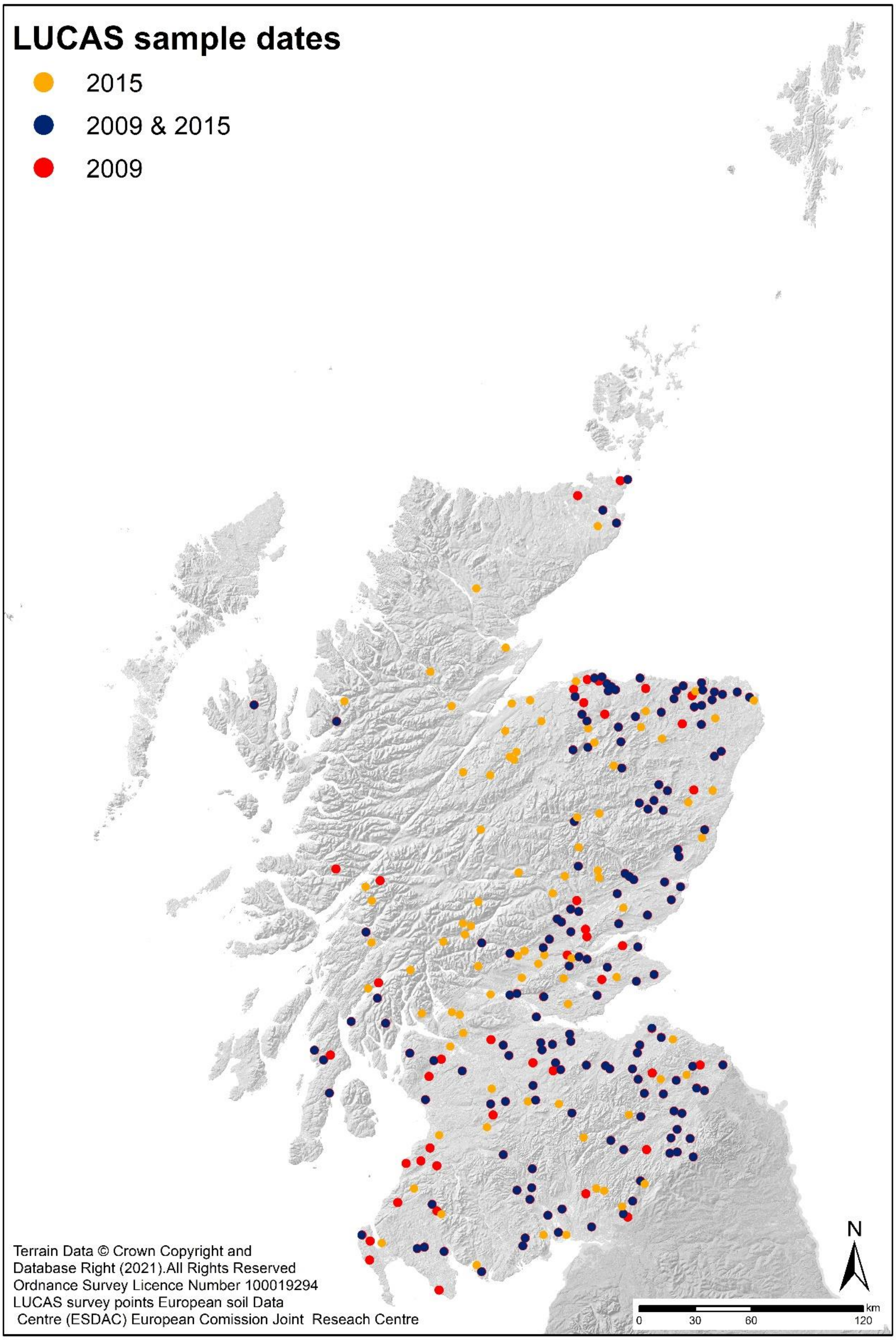

Figure 7: distribution of LUCAS soil sampling points in Scotland from the 2009 and the 2015 sampling campaigns

6.2 SOC stocks in relation to land cover

As seen in Appendix 1, there are few datasets with the necessary measurements to calculate stocks for soils in the open uplands (Table 3). The National Soil Inventory of Scotland (2007-9), the Countryside survey and the Alpine mosaics datasets can be used to calculate stocks. While the Alpine Mosaics dataset is limited to montane environments, the National Soil Inventory of Scotland (2007-9) and the Countryside survey encompass a wide range of upland and lowland habitats.

Table 3: Mean SOC stocks and standard deviations (t C ha^{-1}) of arable land, grassland, semi-natural grassland, woodland moorland and bog to 100 cm depth derived from the National Soil Inventory of Scotland 2007-9.

Land cover	Carbon t ha^{-1}	Number of sites
All	270.3 ± 15.2	179
Arable	111.5 ± 15.6	16
Improved grassland	138.1 ± 21.4	33
Semi-natural grassland	185.2 ± 27.1	26
Woodland	267.5 ± 40.5	26
Moorland	290.8 ± 26.3	46
Bog	528.3 ± 23.0	32

It is worth noting that the Bog category in Table 3 does not take into account the SOC stored in peat below 100 cm. The peat depth data from NatureScot has locations where depths greater than 10 m have been recorded (Figure 8). Work is currently underway to revisit the Chapman et al. (2009) estimates of SOC stocks in peat below 100cm.

The Countryside Survey data shows SOC stocks in a range of broad upland habitats, but it only to 15 cm depth. Typically, organic surface layers in upland peaty soils are greater than 15 cm thick therefore the Countryside Survey underestimates the total stock of SOC in Scottish upland soils.

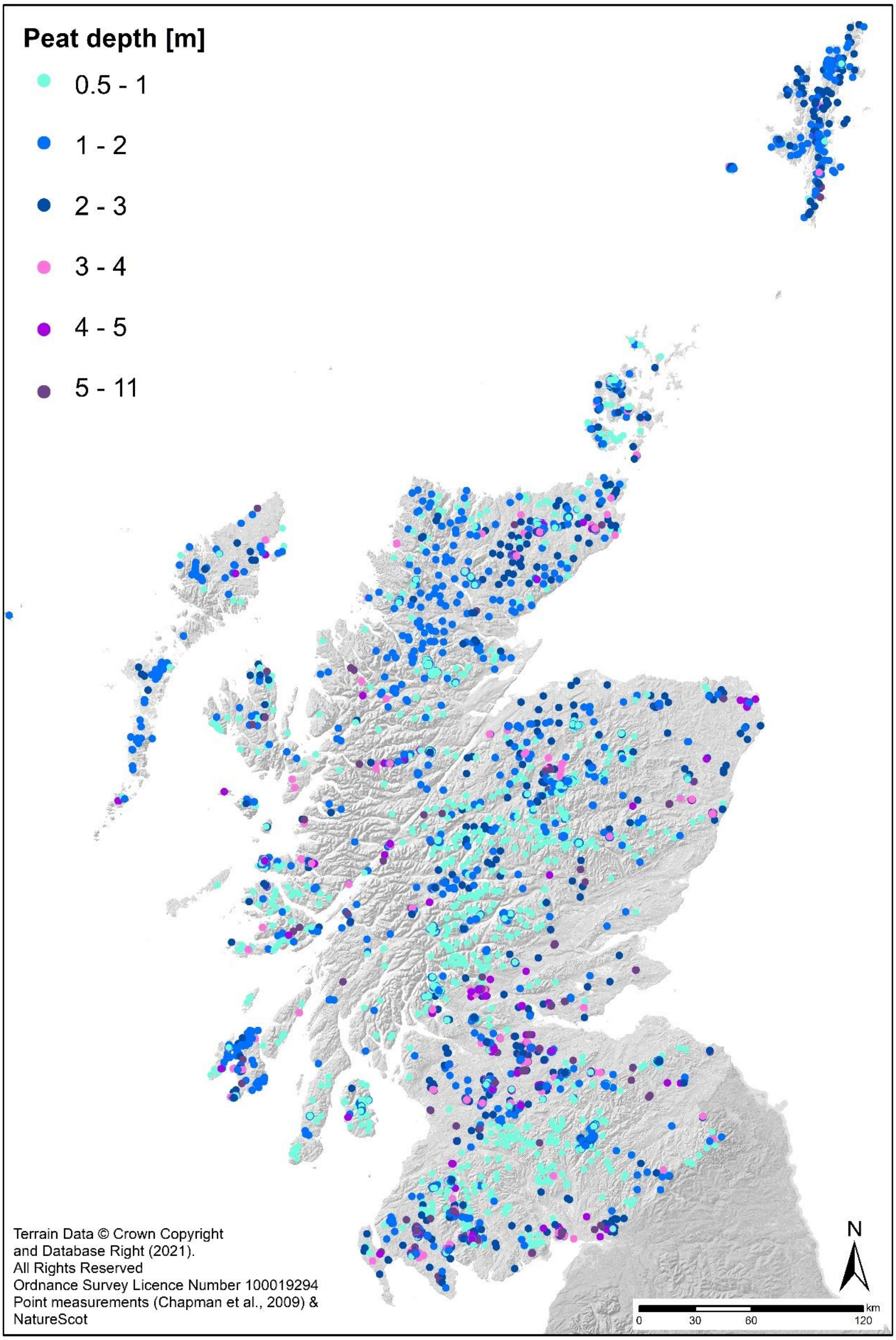

Figure 8: Point measurements of peat depth from Chapman et al., 2009 and NatureScot

7 How has Scotland's soil carbon content changed over time?

There are only a few datasets where the change in SOC concentration or stocks has been quantified. At a national level the main ones are the National Soil Inventories (1978-88 and 2007-9 resampling), the Countryside Survey, LUCAS 2009 and 2015 while the North-east experimental Farm data, 'Woodlands' long-term rotational experiment, Centre for Sustainable Cropping (Balruddery Farm) all provide change data for cultivated soils. Although LUCAS does include a range of land use types, there are large parts of Scotland where no samples were taken (Figure 7). Other substantial change datasets include the Afforested soils dataset for Woodlands and Birse and Robertson Survey for Woodlands, grasslands and Montane habitats.

At the national scale, the NSIS resampling in 2007-9 was specifically designed to assess change in soil properties including SOC stocks and to test sampling methods. Sampling from a soil profile pit, by 0-15 cm core and by 0-15 cm composited auger borings over a 20 m x 20 m square plot. Chapman et al. (2013) reported on the change in SOC between the two sampling campaigns (1978-88 an 2007-9) from the soil profile pits (Table 4). The original location of the samples taken in the first campaign (1978-88) were revisited and resampled. There was an average of 25 years between the original and resampled soils and stocks were calculated to 100 cm. They found no statistically significant change in SOC stocks overall nor within any of the land cover types shown in Table 4 apart from a statistically significant increase in SOC stocks for soils under woodland. They also commented that, had they only measured stocks to 15cm, the results would have shown an increase in SOC stocks overall. It is important to note that, although there was no statistically significant change SOC stocks, changes were detected (Table 4). This included a decline in SOC stocks in improved grasslands. Such differences can act as an early warning but require a larger sample size to assess if there is indeed a statistically significant change.

Chapman et al., 2013 also found a statistically significant decrease (4.03 to 3.7%) in SOC concentration in arable and grassland soils but also that the average thickness of the topsoil had increased from 29 to 32 cm. There was therefore no statistical difference in overall stocks despite the reduction in the mean values of SOC from improved grasslands. The increase in topsoil thickness was attributed to deeper ploughing between the two sampling periods by which the upper portions of the less carbon-rich subsoil were incorporated into the topsoil. This may explain the decline in SOC concentration but also demonstrates the complexities in determining change over time.

A follow up study (Lilly et al, 2016) where moorland soils had undergone afforestation confirmed the increase in SOC stocks in woodlands observed by Chapman et al. (2013).

Table 4: Change in mean total carbon stock (±standard error) between NSIS_178-88 and NSIS_2007-9 (0–100 cm), partitioned by broad vegetation type and after removing peat profiles>100cm.

Vegetation type	1978-88 (C t ha^{-1})	2007-2009 (C t ha^{-1})	Change (C t ha^{-1})	No. sites
All	201.7 ± 11.7	209.8 ± 13.0	8	149
Arable	111.4 ± 16.5	111.5 ± 5.6	0	16
Improved grassland	123.5 ± 9.6	119.0 ± 9.9	-4.5	32
Semi-natural grassland	179.7 ± 25.1	185.2 ± 27.1	5.4	26
Woodland	163.2 ± 24.1	186.7 ± 26.9	23.5	21
Moorland	251.5 ± 20.7	257.7 ± 23.4	6.2	41
Bog	455.0 ± 34.8	489.6 ± 44.7	34.7	13

Emmett et al, (2010) reported that the three Countryside surveys (1978, 1998 and 2007) showed no statistically significant change in SOC concentrations or stocks in the top 0-15cm in Scotland. However, they did see a significant decrease in SOC concentration between 1998 and 2007 from 3.56 % SOC to 3.23 % in the Arable and horticultural habitat but no significant change in stocks Table 5. Since the soils were sampled to a fixed depth then a decline in SOC concentration but no change in stock would suggest an increase in bulk density, that is, a more compact topsoil.

Table 5: Countryside survey change in SOC concentration and stocks in the top 15cm at three time periods.

Vegetation type	Mean SOC % (0-15 cm)			Mean SOC t ha^{-1} (0-15 cm)		
Habitat	1978	1988	2007	1978	1988	2007
Arable and Horticulture	3.58	3.56	3.23*	53.6	52.6	52.3
Improved Grassland	6.46	6.4	6.5	68.8	72.4	70.1

* statistically significant decrease from 1998-2007 sampling

The LUCAS dataset comprises 190 sites sampled in Scotland in 2009 and 234 in 2015 (Figure 7). Of these, 150 sites were sampled in Scotland in both years. These repeat samples encompass a number of habitats that are not always equivalent to those in IACS, NSIS or Countryside Survey. In addition, the 2009 soil dataset does not have the land cover at the time of sampling. Although Table 2 shows the mean values for the two LUCAS sampling campaigns, further data analyses is needed to evaluate this dataset for its ability to detect change over time in SOC concentrations. The time frame of the LUCAS samples means that if the positional accuracy of the samples is sufficient it may be possible to use IACS data to determine the land use history at each site and help quantify the differences in SOC concentration in arable, rotational and permanent grasslands.

In 2017, Lilly et al. (2019) resampled 37 sites in North-east Scotland that had been previously used by the Macaulay Institute for Soil Research to study crop response to P fertiliser in the 1950s up to 1980. A screw auger was used to take samples on a 'W' pattern to a depth of 15 cm as was done previously. The land use varied from cropped fields to long-ley grassland. The original sample was retrieved from the

National Soils Archive and reanalysed for SOC concentration alongside the fresh 2017 samples.

The samples were taken on average 54 years apart and the mean SOC concentrations were 4.19 % (±1.26 %) and 4.48 % (± 1.36 %) for the original samples and 2017 samples respectively. There was no statistical difference between the two set of samples. Although bulk density samples were taken in 2017, none were taken during the original soil fertility experiments. The localised nature of the study and the mixed land uses mean that care needs to be taken when interpreting this dataset alongside other national scale assessments as they are not directly comparable. The fixed depth sampling means that any possible increase in topsoil thickness was not assessed and, while topsoil thickness was measured in 2017 (providing a basis for future sampling), it was not during the original fertility experiments.

The Centre for Sustainable Cropping (CSC) at Balruddery Farm has samples from 6 arable fields collected annually since 2010 on a 18m grid pattern and at 0-20 cm (350 samples per year). This dataset provides a detailed estimation of both spatial and temporal variability in SOC concentrations.

It is clear from the list of datasets in Appendix 1 that few were collected specifically to investigate change in SOC over time, but it is possible that many could be adapted to do this. As the original sampling was done for many different reasons and designed to answer a different set of questions, care would be needed in deriving a clear set of protocols to maximise the information that could be derived. While it is better to have consistent datasets with specific sample designs, protocols and at an appropriate scale to answer specific questions on SOC, concentrations, stock and storage potential, the existing datasets could be used to give rapid, interim measures of change and also help in establishing sample densities for a monitoring scheme. Robust statistical advice would also be needed to establish if datasets could be amalgamated.

8 What is the potential for Scotland's soils to store more, or to lose carbon?

In a report to ClimateXchange (CxC) Yeluripati et all. (2018) wrote that the '*amount of carbon that accumulates in soil is finite*'. Using evidence from long-term experiments a Rothamsted Research station, Poulton et al. (2018) showed that the annual rate of soil carbon accumulation is non-linear (Figure 9) with greater SOC accumulation observed soon after the land management or land use change and slowing as the soil reaches a new equilibrium. Their observations were carried out over 160 years of recorded soil management practices. What was also clear was that the initial SOC content determines the rate at which SOC accumulates.

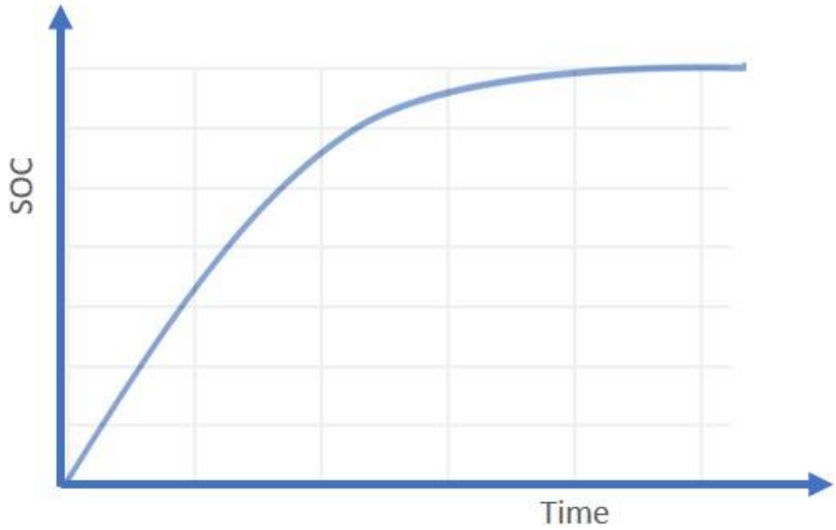

Figure 9: Schematic representation of SOC sequestration over time

The work by Poulton et al. (2018) was with respect to the 4 per mille initiative where land managers are encouraged to increase SOM stocks by 0.4% per year and their conclusion was that, while possible, the management practices required were not practicable. Minasny et al. (2018) reviewed soil sequestration rates from 20 case studies around the world and concluded that '*In regions with high inherent SOC content, it may prove difficult to further increase their C levels, as these areas may already have reached equilibrium with current practices.*' This proves to be a complex issue and requires a thorough and rigorous evaluation of the relevant literature.

8.1 Estimating potential losses or gains of SOC from observed data

In 2013, Lilly and Baggaley took a simpler approach to evaluating the potential for Scottish cultivated topsoils to store additional SOC. This evaluation was based on the SOC concentrations in the Representative Soil Profile dataset. The observed median (middle value of the data), minimum and maximum SOC concentration of mineral topsoils were determined for each of the soil 313 individual soil types shown on the National Soil Map of Scotland (Soil Survey of Scotland Staff, 1981) and were deemed to be cultivated using a land cover map. The topsoil SOC stock was then calculated for each of the soils using estimated horizon thickness and predicted bulk densities. The Potential to gain SOC was then calculated by subtracting the median value for the maximum and the potential to lose SOC was calculated by subtracting the minimum SOC concentration from the median (Figure 10).

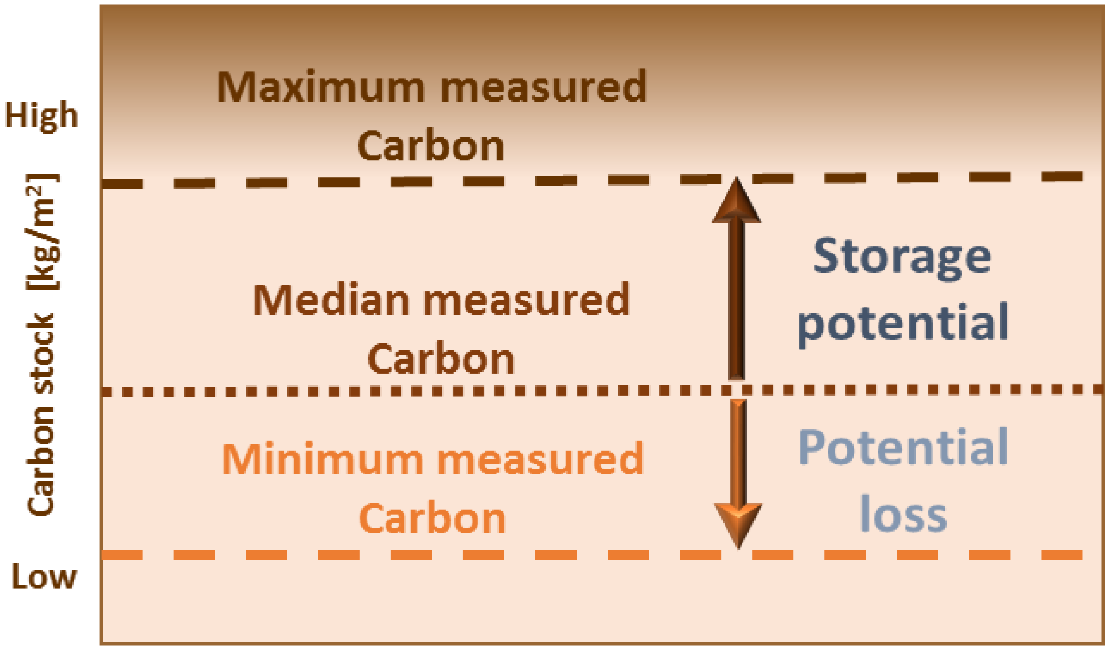

Figure 10: Graphical presentation on method to calculate potential Soc gains or losses.

They estimated that there was the potential to store an additional 174 Mt C but there was the potential to lose 112 Mt C if SOC concentrations fell to the minimum value observed for each soil type in the database. They mapped both the potential losses and potential gains (Figure 11) on what was the most up to date digital version of the Soil map of Scotland.

Later they modified this evaluation to calculate potential gains and losses for grasslands and arable land separately (Yeluripati et al., 2018). They estimated that the potential additional storage capacity for grasslands was 60 Mt (range 48-86 Mt) and for soils under arable it was 88 Mt (range 78-104 Mt). However, this was based on an assumption that soils under grassland had, on average 1.4% SOC more than arable land which is slightly more than shown in Table 1.

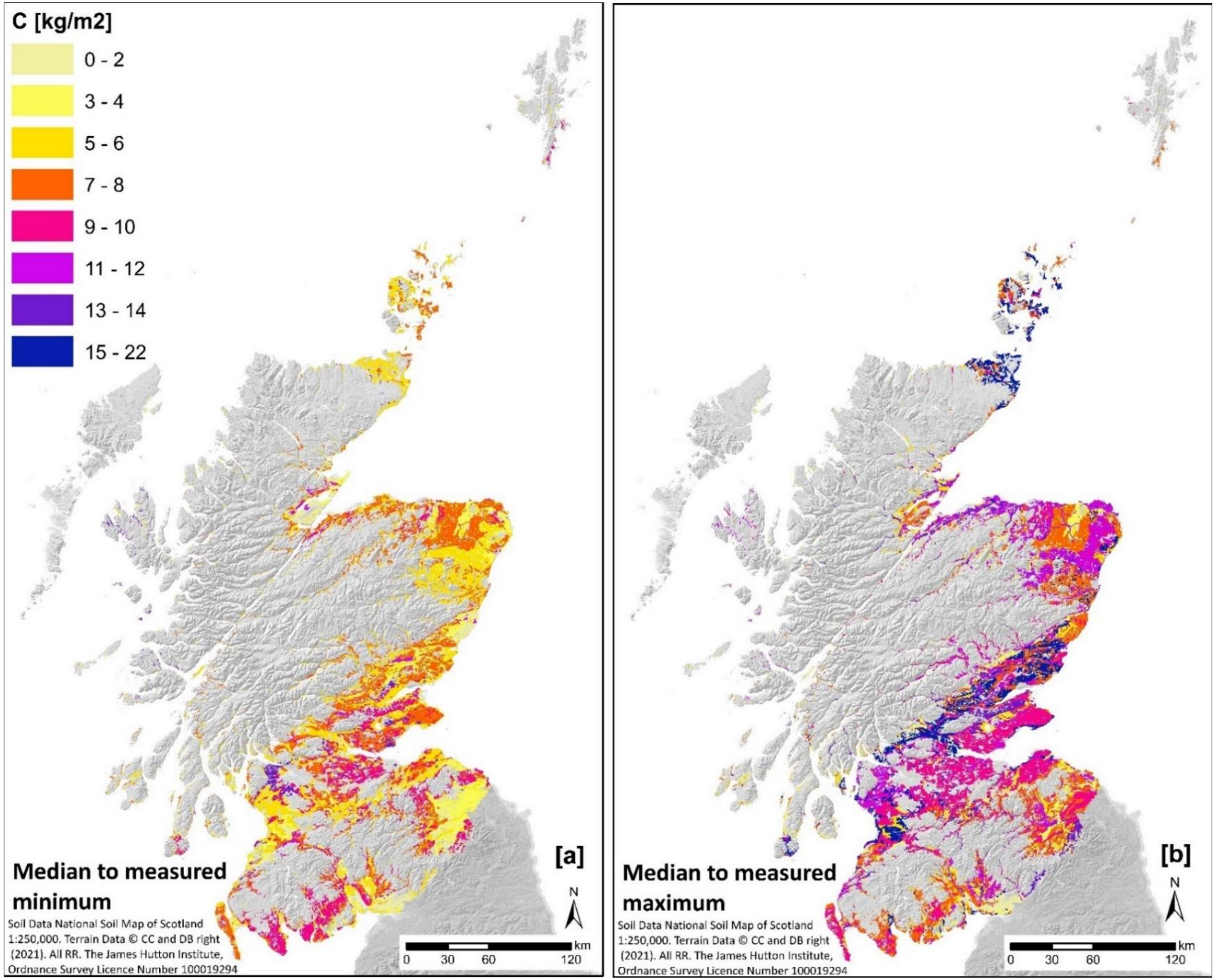

Figure 11: Maps showing the potential for Scottish soils to gain (a) or lose (b) soil carbon (Lilly & Baggaley 2013)

Even with this approach key questions remain: are the observed maximum and minimum values the actual maximum and minimum, how long would it take to reach the maximum and what management practices are required to increase SOC stocks, how long would it take to reach the minimum and what management practices would lead to a decrease in SOC stocks? While there are simple ways to estimate the absolute minimum SOC content based on the proportion of fine silts and clays in the soil (for example, Hassink et al.,1997; Paterson et al., in press) the maximum value is much more difficult to determine.

In 2019, Yeluripati et al. produced a list of practices to sequester soil organic carbon in agriculture soils. They assessed their feasibility for Scottish conditions and gave estimated rates of sequestration. The list included reduced or no tillage, increased residue returns, fertilising and liming, crop rotation and organic manures, catch crops and changes in grazing intensity.

8.2 Impact of land use change on SOC

The role of land use change in both the loss and gain of SOC is complex with often conflicting evidence. Recent reports and papers (Smith et al., 2004; Rees et al., 2017; Yeluripati et al., 2018; Lilly et al., 2020) have attempted to collate existing information but it is clear that there are few data specifically on Scottish and/or UK soils. Some of the data do support the supposition that conversion to arable production systems can lead to a loss of SOC, while increasing the length of time a soil is under grass tends to lead to gains in SOC (Rees et al., 2018). Table 6 summaries some of the like likely impacts on SOC due to land use changes but this is a considerable simplification and within different land uses, different management practices can also influence both the rate and amount of SOC sequestration or loss. There is also conflicting evidence in upland systems, for example, the conversion of moorland to forestry. Lilly et al. (2016) reported an increase in SOC stock after a period of between 12 and 57 years since planting but Friggens et al. (2020) reported either loss or no change in SOC stock after 12 and 39 years.

Much of the literature is concerned with measuring the impacts of land use change and less so with changes due to different management options. There is a considerable number of papers that report changes in SOC with land use change. A search of an online database of scientific papers published since 2010 for the terms '*Soil carbon sequestration AND grassland*' for papers, produced over 1800 results which were reduced to 870 when studies from South American and Asian countries were removed. A similar search for papers on '*arable*' rather than grassland yielded over 500 papers, reducing to 340 when studies from South American and Asian countries were removed. While many of these are unlikely to provide sequestration rates or potential losses due to land use change specific to Scottish conditions, it would need a considerable effort to review and identify the ones with meaningful data to answer the question on the impact of land use change on Scottish soils, and importantly, the management practices that influence SOC contents.

Table 6: Likely direction of change of SOC contents due to a change in Land use (adapted from Smith et al., 2004; Rees et al., 2017; Yeluripati et al., 2018; Lilly et al., 2020)

From / To	Arable	Grassland	Semi-natural grazing land	Agroforestry	Forestry
Arable		↓	-	-	↓
Grassland	↑		↓	-	↑↓
Semi-natural grazing land	-	↑		-	↑↓
Agroforestry	↑	↑↓	-		↑↓
Forestry	↑	↑	↑↓	-	

Note: ↑ SOC increase; ↓SOC decrease; ↑↓ Can be either increase or decrease; - no information

9 Online tools to visualise SOC

There are existing online tools designed to help manage soil carbon, for example, one tool hosted by the Hutton, 'Topsoil organic matter comparison tool' (https://om.hutton.ac.uk/) shows the typical organic matter content of soil at any location in Scotland. This tool was derived from SIfSS ('Soil Indicators for Scottish Soils' - http://sifss.hutton.ac.uk/) also hosted by the Hutton. Both use summary data (for example, averages, minimum and maximum) derived from the Representative Soil Profile dataset and the underlying National Soil Map to identify the individual soil types. Users can zoom in to identify individual fields. These tools allow users to input their own, measured SOC or SOM values and see how it compares to the national average for that soil type. Some of the disadvantages of these tools are that they rely on averaged data that were collected over a long period of time and the scale of the underlying map (1:250 000). There is online guidance to help users select the correct soil type at any locality.

Ways to improve this dataset would be to use the Soil Map of Scotland (partial cover) which is based on 1:25 000 scale soil maps and shows more detail in terms of the soil types and their distribution. Digitising of this map series is still underway as is the collation of soil property data (including SOC concentrations) for each soil type. However, a hybrid map showing the improved resolution data, where available, combined with the national cover map would be an interim measure.

As well as SIfSS and the Topsoil organic matter comparison tool, Scotland's Soils Website (https://soils.environment.gov.scot/) also shows a range of soil properties including SOC, SOM and LoI for the soils shown on the National Soil Map of Scotland (1:250 000). Users can also zoom in to this dataset to identify individual areas of interest.

The James Hutton Institute, in partnership with Quality Meat Scotland, has produced a smart phone app called SOCiT (Soil Organic Carbon information) that provides farmers with a quick, cost-effective source of information about the organic matter content of their soil. After digging a shallow hole to expose the topsoil, a user can take a picture of the soil with a smart phone or tablet. The app uses the smart phone or tablet's GPS to record the user's position. within the photograph of the soil. This information is then sent to the Hutton servers where the SOC concentration is estimated. This estimate is based on a statistical model that uses data from the Representative Soil Profile Dataset combined with the topsoil colour from the photograph.

Although not confined to SOC and aimed at evaluating the impact of woodland expansion on above and below ground SOC, the online tool '*Mapping net change in carbon from afforestation in Scotland*' is an interactive tool where different trees species and management options can be explored. The tool shows the modelled change in net carbon over a 100-year period.

10 Novel technologies

FTIR (Fourier Transform Infrared) Spectroscopy is a non-destructive analysis technique, using an infrared sensor (from the mid infrared region), which can be used to characterise a wide range of materials, including soil. Infrared radiation is absorbed at specific frequencies depending on the chemical composition of the sample which allows producing a chemical "fingerprint" or chemical profile (IR spectrum). For soil analysis the overall chemical profile includes information about both the organic and mineral components. Therefore, the IR spectrum provides an instant insight into the proportion and nature of clay minerals and allows a rapid assessment of the relative amount and nature of the soil organic matter.

FTIR spectra can provide an effective method for prediction of soil parameters using statistical methods that correlate IR spectra to soil properties. Multiple soil properties can be predicted from a single spectrum (for example, %C, %N, pH, bulk density) and therefore the method allows rapid and economical monitoring of soil. In the Lab, prediction of dried milled soil by FTIR has been found to be very accurate when compared to the usual analytical methods. It has been shown to be more accurate than the more widely used technique, NIR spectroscopy, which uses a slightly different frequency range.

A field-based FTIR analysis method, using a handheld instrument, could potentially be very useful for on-farm SOC analysis. Such a method, using a novel sampling accessory, is under development at the James Hutton Institute. However, there remain some challenges to overcome such as being able to account for soil spatial heterogeneity (a problem for all soil sampling), variable moisture content and differing soil textures. In addition, there is a requirement for good spectral libraries (datasets) to get sufficient representation for reliable predictions. Once operational this method could be used both for the soil analysis/ monitoring of SOC but also as a management tool – deployed on farms to assess how current practices are impacting on SOC.

Development of reliable spectroscopic analysis of soil using the mid infrared region is the subject of a global working group on soil spectroscopy recently set up by the FAO under their GLOSOLAN umbrella http://www.fao.org/global-soil-partnership/glosolan/soil-analysis/dry-chemistry-spectroscopy/en/

Although with the handheld FTIR method, samples could be analysed *in situ,* there is still a requirement to dig a pit to assess SOC % below the topsoil. However, one of the other advantages of using the FTIR technique is that prediction of undisturbed bulk density, needed for calculating C stocks, can also be done reliably by FTIR on the same IR spectrum.

There are also wider benefits to FTIR spectral analysis of soils in that information on the chemical composition the SOM can be gained from interpretation of the IR spectrum of a soil and FTIR spectra can also be linked to soil properties/functions such as available water capacity.

11 The co-benefits of SOC

Soil carbon in important for keeping Scotland's soils healthy and maintaining a good nutrient supply to growing crops, it promotes a good and stable soil structure that retains water for crop growth and improves infiltration. In cultivated soils, maintaining or increasing SOC concentration is therefore important for mitigating the effects of climate change.

Our cultivated topsoils can already hold around 3274 billion litres of water that crops need to grow but if we could increase the carbon content by the amount estimated by Lilly and Baggaley (2009) which was 174Mt C, then we have estimated that topsoils would retain an additional 109 billion litres of water, the equivalent of 6mm of rainfall over all of the cultivated land and helping make Scottish soils more resilient to drought.

Datasets like the NSIS 2007-9, Soilbio and some specific research projects have data on soil moisture retention and bulk density as well as SOC concentrations so the relationship between these properties and SOC can be examined (for example, see Appendix 3). Greater water retention will increase the water that is held in the soil after rainfall events, and a reduction in bulk densities will improve infiltration, both of which will reduce runoff. Meanwhile, increasing the stability of the soil aggregates will prevent smaller particles from being preferentially eroded.

There is a lack of data in Scotland on the relationship between SOC and erosion. One of the most widely used assessment of soil erosion is the Universal Soil Loss Equation first developed in the USA (Wischmeier and Smith, 1978). However, this model was developed in area with SOC concentrations much lower than is found in Scotland and therefore is relatively poor at modelling the erosion rates in Scottish soils. The model is also driven by rainfall intensity, however, in Scotland erosion has occurred due to prolonged low intensity rainfall, high intensity rainfall and snow melt (Lilly and Baggaley, 2015). While aggregate stability is important for limiting soil erosion, the ability of the soil to absorb rainfall or snowmelt before becoming saturated is perhaps more important in Scotland (Lilly and Baggaley (2015).

12 Conclusions

Scotland has a wealth of soil data, due its long mapping and soil characterisation programme and soil research, primarily Government funded. However, most of the data were collected for purposes other than evaluating SOC contents and have been adapted to estimate SOC stocks and to measure change over time. Some of the datasets were collected using the same or similar protocols while others used different sampling protocols. A thorough, statistical examination of the various datasets may be able to determine their potential to further assess change over time, to assess SOC contents by land use or to guide any future monitoring of SOC.

Scottish soils are relative rich in SOC which potentially makes sequestering more SOC more difficult. Work by Lilly and Baggaley (2013) also showed that there is also the potential to lose a considerable amount of SOC from Scottish topsoils. Therefore, as well putting measures in place to increase SOC, there should be measures to protect existing stocks. This is especially important in the organic and organo-mineral soils of the hills an uplands which hold 66% of the SOC stocks in the upper 100 cm.

Some of the datasets identified have data spanning a number of years and consequently have SOC concentrations measured by different analytical techniques and equipment. Correction factors have been developed to standardise these SOC concentrations though this has not yet been applied to all the stock estimates.

Although maps provide a useful overview of the spatial distribution of soils with different SOC concentrations, they can be limited by the scale they were produced at. Online tools are valuable as they can allow the user to view information on variability that cannot be represented on an individual map. Online tools with the same underlying data are more useful in that a user can zoom in to specific fields or locations to get an estimate of the SOC concentrations, however, zooming-in does not change the resolution of the map.

There are some datasets available to assess change in SOC contents or stocks over time though few were specifically designed for this purpose. These data sets can seem to give conflicting results on the nature of change. However, this is partly due to differences in sampling protocols (fixed depth vs whole soil) but also to the limited sample size for some land uses. To be statistically robust large sample sizes are often needed, especially when trying to identify statistically significant small changes. This is important as SOC changes over long periods of time.

Field-based Infra-Red spectroscopy techniques are not yet able to provide robust and consistent measurements of SOC in the field but once operational this method could be used both for the soil analysis/ monitoring of SOC but also as a management tool – deployed on farms to assess how current practices are impacting on SOC. Work in ongoing to develop these methods and reduce the uncertainties in predictions.

Finally, there are many co-benefits to increasing SOC in soils besides mitigating climate change. SOC promotes the development and maintenance of soil structure and porosity which leading to improved water retention to maintain the growing crop and infiltration to reduce runoff thereby helping to reducing the risk of erosion and down-stream flooding. SOC is also important for maintaining soil biodiversity including organisms such as bacteria, fungi, insects and worms. These organisms help maintain a healthy functioning soil and have a role to play in nutrient cycling and pest control. Achieving these goals will also help mitigate the effects of a changing climate.

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Appendix 1. Soil datasets with measurements of soil organic carbon of Scottish soils
(* denotes datasets that are component parts of the 'Scottish Soils Database' held by the James Hutton Institute)

Datasets		Number of sites	Extent	Land Use Specific	Strengths	Weaknesses
1	Representative Soil Profiles of Scotland *	~14000	National	No	Extensive dataset covering most of Scotland especially cultivated land. Collected over a long period of time with bulk of samples taken 1970s and 80s but still being added to. Sampled by horizon to 100cm and Has measurements of SOC and LoI for topsoils and subsoils. Data can be linked to soil maps to show spatial distribution of SOC.	Collected over a long period of time from 1940s with bulk of samples taken 1970s and 80s. Different methods used to determine SOC concentrations during this period. Soils subjectively sampled to characterise soil map units. Very few measurements of bulk density to calculate stocks.
2	National Soil Inventory of Scotland (1978-88) *	721	National	No	Extensive dataset covering all of Scotland at 10km intervals. Objectively sampled Inventory. Soil horizons sampled	Slight weakness is the time frame taken to complete the survey (10 years). No direct measurements of

	Datasets	Number of sites	Extent	Land Use Specific	Strengths	Weaknesses
					to 100cm. SOC and LoI measured	bulk density to calculate stocks.
3	National Soil Inventory of Scotland (2007-9) *	183	National	No	A subset of the National Soil Inventory of Scotland (1978-88) resampled in 2007-9 on a 20km grid. Soils sampled by horizon to 100cm. SOC and Loi both measured as well as bulk density. Was used to assess change over time.	Less extensive than the first Inventory, 25% of those sites revisited.
4	Countryside survey	195	National	No	Based on classification of 1km squares into 'ITE' land classes that represent major environmental gradients and habitats in the UK. Soils sampled 3 times (1978, 1998 and 2007 at a depth of 0 -15cm. LoI measurements.	Only sampled 0-15cm and bulk density data only available for 2007. The samples are taken from different locations within the 1km square each time.
5	Geochemical Baseline Survey of the Environment	~40,000	Regional	No	Composite soil sampled every 2 km^2 at depths 0-20 and 35-50cm. Greater density in Urban areas.	Only Loss on Ignition for limited parts of Scotland

	Datasets	Number of sites	Extent	Land Use Specific	Strengths	Weaknesses
6	Scottish Soil Fertility database	~180,000	Regional	Cultivated soils	Data from 1996. Composite field-scale sample 0-20cm for arable and 0-10 for grasslands. LoI measured primarily for Liming requirements. Data also available for James Hutton Inst. farms.	Spatial reference is to postcode of the submitter, not the field. Data ‘owned’ by the submitter.
7	LUCAS _2009	190	Regional	Primarily cultivated soils	Composite topsoil samples taken 0-20cm on a predetermined sample frame. SOC measured.	Topsoil only. Mainly cultivated land with a small sample of other land uses. No measured bulk density or topsoil thickness.
8	LUCAS _2015	234	Regional	Primarily cultivated soils	Composite topsoil samples taken 0-20cm on a predetermined sample frame. SOC measured. 150 of the original sites resampled.	Topsoil only. Mainly cultivated land with a small sample of other land uses. No measured bulk density or topsoil thickness.
9	SoilBio	5152	Regional	Cultivated soils	Recent topsoil LoI data with a subset of soils with bulk density and water retention.	Topsoils only mainly from arable soils. Limited

	Datasets	Number of sites	Extent	Land Use Specific	Strengths	Weaknesses
					Also has management data.	distribution of sites.
10	NE experimental Farm	37	Regional	Cultivated soils	Samples of former (mainly 1950s) experimental plots taken resampled in 2017 at 0-15cm to assess change in SOC concentration. Bulk density measurements and topsoil depth also taken so stocks can be calculated.	Limited to North-east Scotland and small dataset.
11	Scottish soil map unit transect study *	6 transects (64-138 sites	Local	Cultivated soils	Soils sampled in 1988 at 0-15 and 40-50cm (unless cuts across horizons) on a transect with regular intervals of 5 and 10m to assess soil variability in extensive soil types. Useful for assessing variability in SOC for designing sampling schemes	Soils sampled in 1988. Only one had topsoil bulk density measurements.
12	'Woodlands' long-term rotational experiment at Craibstone	?	Local	Cultivated soils	Arable fertiliser treatment experiment started in 1922, occasional	Only occasional measurements of SOM are available.

Datasets		Number of sites	Extent	Land Use Specific	Strengths	Weaknesses
					measurements of soil organic matter	
13	Water stable aggregates	203	Local	Cultivated soils	150 of the samples taken 0-5cm in 2009-10 have SOC measurements from the Lunan catchment and 50 have SOC from the Tarland catchment taken in 2012	Limited to 2 Catchments
14	Rainton Farm	214	Local	Cultivated soils	Derived SOM values from a number of fields starting in 1996 to present. Farmer has made data publicly available.	Limited to 1 farm
15	East of Scotland Farm Survey	105	Regional	Arable land	Triplicate 0-15cm taken in 2007 and SOC measured, bulk density core taken adjacent to the sample.	No indication that topsoil thickness was measured
16	Barley Soils	50	Local	Arable land	Soils sampled in Spring/autumn 2016 at 0-15cm	Limited to only 5 fields
17	Balruddery Farm Grid survey *	124	Local	Arable land	Soils sampled in 2008 and some later in 2014 on Berryhill Farm at 0-15 and 40-	Limited to Balruddery Farm.

	Datasets	Number of sites	Extent	Land Use Specific	Strengths	Weaknesses
					50cm on a 100m grid. SOC and LoI measured at both depths.	
18	Mylnefield Farm Grid Survey *	325	Local	Arable land	Soils sampled in 1987at 0-15 and 40-50cm on a 25 and 100m grid. SOC and LoI measured at both depths.	Limited to Mylnefield Farm. Some land no longer available.
19	Centre for Sustainable Cropping Balruddery Farm	350 (6 fields)	Local	Arable land	Soils sampled annually beginning in 2010 on a 18m grid at 0-20cm depth. SOC data available and limited bulk densities,	Main focus is on arable production systems and limited to 6 fields.
20	Glensaugh agroforestry plots *	190	Local	Pasture to agroforestry	Soils sampled in 1987at 0-15 and 35-45cm on a 10 and 50m grid prior to establishing agroforestry experimental plots. SOC and LoI measured at both depths. Partial resampling in 2012 with bulk density measurements made.	Underwent a land use change from pasture to agroforestry. Some trees removed.

	Datasets	Number of sites	Extent	Land Use Specific	Strengths	Weaknesses
21	Grid Surveys in Scotland *	8 grid surveys (19-1214)	Local	No	Various dates. Some soils sampled by horizon to 1m and some fixed depth. Grid intervals from15-400m. One site (Hartwood) has topsoil SOC and bulk densities	Only 3 have SOC measurements, one upland and two lowland. Limited number of samples in each, between 10 and 90.
22	UK Soil and Herbage Survey	56	Regional	No	Three 0- 5cm soil cores taken at 3 locations within a 20 x 20 m square in 2001/2 and bulked providing 3 samples 6 x 5cm samples taken from each site for bulk density and SOC. Includes urban areas	50 km grid
23	Environmental Change Network – soil *	3	Local	No	Started in 1993 and repeated on 5- and 20-year cycles. Complex sampling protocols including auger borings and full profile pits. SOC measured every 5 years and bulk density every 20 years.	2013 profile pit sampling was not done.

	Datasets	Number of sites	Extent	Land Use Specific	Strengths	Weaknesses
24	Afforested soils *	39	National	Afforested soils	Soils sampled in 2013 by horizon to 100cm and by fixed depths. Resampling of soils that underwent afforestation. SOC, LoI and bulk densities available so stocks can be calculated	Only includes sites that were moorland before trees were planted.
25	SNH woodland exclosures *	12	Regional	Woodland	6 paired sites inside and outside of exclosed woodland. Sampled in 2014. Mineral subsoil sampled by horizon and whole thickness of organic layers sampled. LoI, C and bulk density measured	Only Brown earth soils samples and limited sample size
26	ITE/NCC 'Bunce 1971' woodland survey	103 (across GB)	National	Woodland	Started in 1971 and repeated in 2000-3. 0-15cm sample from a 200m^2 plot. SOC measured.	Litter layer not sampled.
27	Level I Forest Conditions survey	67 (across UK)	National (UK)	Woodland	Started in 1994, composite soil samples at 0-5, 5-10, 10-20cm.	Scheme replaced by BioSoil.
28	Level II Intensive Monitoring of Forest Ecosystems	10 (across GB)	National (UK)	Woodland	Baseline soil sampling in 1995 including SOC	Mainly aimed at solute chemistry.

	Datasets	Number of sites	Extent	Land Use Specific	Strengths	Weaknesses
29	BioSoil	69 in Scotland	National	Woodland	Started in 2006 with soils sampled at fixed depths of 0-5, 5-10, 10-20, 20-40 and 40-80cm. Organic layers sampled separately. SOC, bulk density and depths recorded so stocks can be calculated.	Woodland sites only and fixed depth samples can mean that horizons are mixed perhaps diluting SOC concentrations.
30	Birse and Robertson Survey soils *	660	National	Woodland, grassland, montane	Soils initially sampled as part of Soil Survey of Scotland sampling programme between 1945 and 1985. Resampled in 2011-2013 for grasslands, 2007 for woodlands, 2004-2006 for montane. Sample depths variable depending on habitat. SOC and bulk density available from all habitats/	Samples were purposively selected.
31	Trends in pollution of Scottish Soils	30	National	Moorland	First sample in 1990, repeated 1990 and National Inventory 2007-9 data used for repeat in 2010. Soils	Restricted to soils under heather moorland.

	Datasets	Number of sites	Extent	Land Use Specific	Strengths	Weaknesses
					sampled 0-5cm on three transects across Scotland at roughly 20km intervals. SOC and LoI measured.	Primarily organic horizons.
32	MOORCO (Moorland Colonisation)	10	Local	Moorland	One set of experimental plots establish in 1975 and has SOC, bulk density and horizon thickness data. Others established 2005 with bilk density and surface layer SOC measurements	Mixture of treatments on relatively small plots.
33	Alpine Mosaics *	99 (35 soil profiles)	Local	Montane	Soil profiles sampled in 2018/9 by horizon to 100cm where possible. Horizon thickness, bulk density and Soc data available to calculate stocks.	Only upland, montane soils.
34	Racomitrium Heath Survey	17	Local	Racomtrium heath	Composite soils samples at 0-4cm taken in 2006 and 0-15cm core samples in 2011. Both have SOC measurements.	Very restricted habitat.

	Datasets	Number of sites	Extent	Land Use Specific	Strengths	Weaknesses
35	Scottish Peat survey	140 sites (number of sample points not recoded)	National	Peat deposits	Earliest samples 1956. Multiple depths up to 1100cm. Peat volumes calculated for each site along with carbon concentrations. Grid survey at intervals between 25 and 100m. Samples taken at depths of approx. 50cm intervals.	Originally the surveys were to identify exploitable peat resources for power stations.
36	Glensaugh Peat depth survey	96	Local	Peatland	Soils sampled in 2005 on a 200m grid at fixed depths of 0-15, 15-30 and 50-65cm. SOC and bulk density data available. Peat depths recorded.	Bulk density from sample cut from Russian auger.
37	Forsinard	40	Local	Peatland	Composite surface organic layer 0-5cm sampled in 2011 and 2017. FTIR analyses may give C concentrations	Limited sampling of specific habitat. Protocols changed.

Appendix 2: Information on recent methods to calculate carbon stocks in Scottish soils

Mapping soil carbon stocks based on 1:250,000 soil map polygons (Baggaley et al., 2016, Lilly & Baggaley, 2013)

Soil profiles are classified as soil series based on their morphological characteristics. When soils were mapped at the 1:250 000 scale, polygons were drawn around landscape units with a distinctive set of soil types (Soil series). For each soil series the horizon characteristics such as sand, silt and clay content, carbon concentration, horizon depth and stone content will vary. These characteristics will also vary depending on whether the soil is under cultivation or not.

Representative soil profiles were derived for each soil series within the 1:250 000 National Soil Map of Scotland for both semi natural and cultivated land uses. The average and range of carbon concentration, based on data from 6000 soil horizons held in the Scottish Soils database, was then calculated for each soil horizon (layer) for each soil type. Using bulk density data from a smaller number of horizons where data were available, a regression equation was derived relating it to soil texture and carbon concentration along with the uncertainty in the relationship. Soil carbon stocks for each soil type were calculated by multiplying the soil bulk density, carbon concentration and horizon depth together, correcting for stone content and summing to 1 m depth. The total stock for Scotland was determined by multiplying the stocks for each soil type by the area of Scotland where the soil occurs, and then summing these contributions from each soil type. The uncertainty in these estimates was calculated using a statistical method that accounted for the variability in the soil carbon concentrations (based on the number of points available for each horizon and the standard deviation of measured concentrations) combined with the uncertainty in predicting the bulk densities using a regression equation. This analysis showed the importance of the accurate prediction of bulk densities when calculating soil carbon stocks and is something that is currently being further investigated.

Mapping soil carbon stocks based on geostatistical modelling (Poggio & Gimona, 2014)

The modelling was done in two steps, both of which have uncertainty associated with them. Bulk density was measured for 900 horizons from the National Soil Inventory of Scotland (2007-2009) dataset. These data were used to develop a model to predict the volume of soil (bulk density corrected by the volume of stones) based on the more widely available measurements of pH and organic matter. The predicted volume of soil was multiplied by the measured carbon concentrations at 19,500 soil horizons to calculate carbon stocks (75% of the total available). A model was then developed between soil carbon stock in each of the soil horizons from the Scottish Soils Database and the terrain and satellite-derived variables. The model was used to interpolate the calculated carbon stocks in 3 dimensions: 5 cm layers in each cell on a 1 km grid to those locations where there were no measurements. The model that was used involved an approach defined as Generalized Additive Models exploiting the neighbouring soil properties values in both lateral and vertical space. A further correction was applied using a method (error kriging) that tries to minimise discrepancies between the estimates and the observations

The uncertainty was calculated with a large number of iterations of the model with slightly different spatial configurations of the data. This produced a range of values for each 5 cm layer within each 1 km square that were summarised and provided a measure of uncertainty. The model outputs were validated by comparison of the predicted values with the values available from the 25% (6500) soil horizons not used to build the model. This important step provides a more robust assessment of the results and uncertainty obtained.

Mapping soil carbon stocks based on neural network modelling (Aitkenhead & Coull, 2016)

This method used two steps. The first was to generate a neural network model that predicted soil carbon density (soil carbon percentage multiplied by bulk density) from Loss on Ignition (LOI) data and depth. This was developed using the National Soil Inventory of Scotland (2007-2009) dataset where all three parameters had been measured. A second neural network was then developed based on a larger number of points to predict LOI and profile depth from variables that influence soil formation and distribution in the landscape, in this case topography, land cover, data from the soil map, rainfall and temperature. This spatial model was then applied to predict LOI at every 1 cm depth interval to the maximum modelled depth in 100 m grid cells across Scotland where it had not been measured.
The range of values for each grid cell and at each depth within those cells was calculated as a result of validating the model against measured stocks that were not used in the model development. This range is a function of the inherent variability of soil carbon in the landscape, imperfections in the model (no statistical approach can fully capture the relationships expressed by reality) and the fact that not all explanatory variables can be included in any modelling approach. In some cases large uncertainty limits are due to the application of two different neural networks to the data due to the smaller number of points where bulk density had been measured.

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Appendix 3: Plots of SOC concentrations against selected soil properties

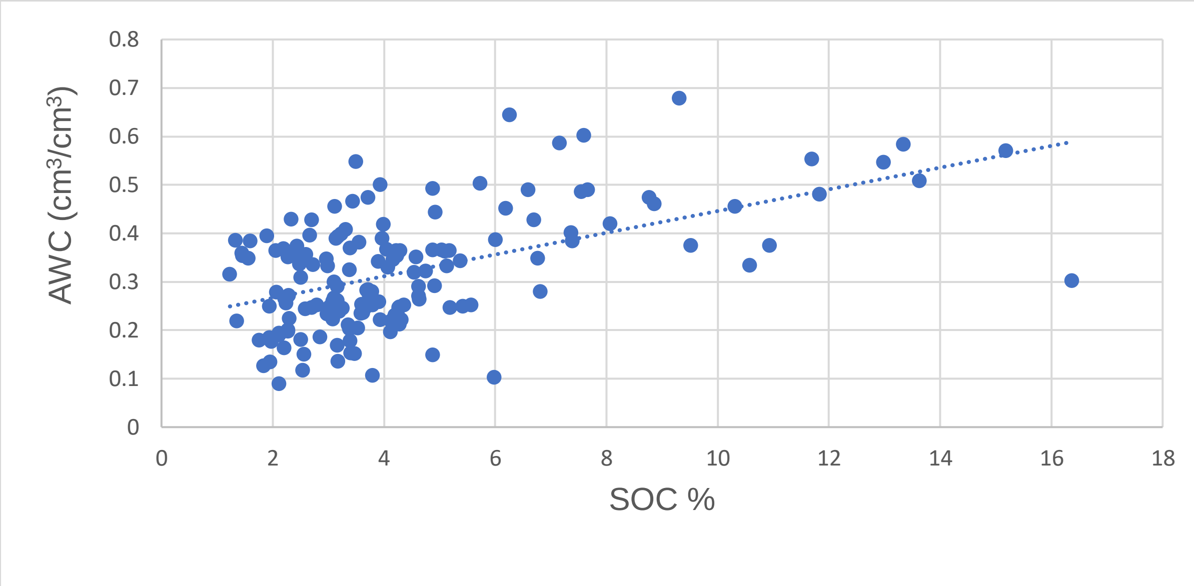

Figure A1: Relationship between SOC concentration and Available water capacity from NSIS 2007-9.

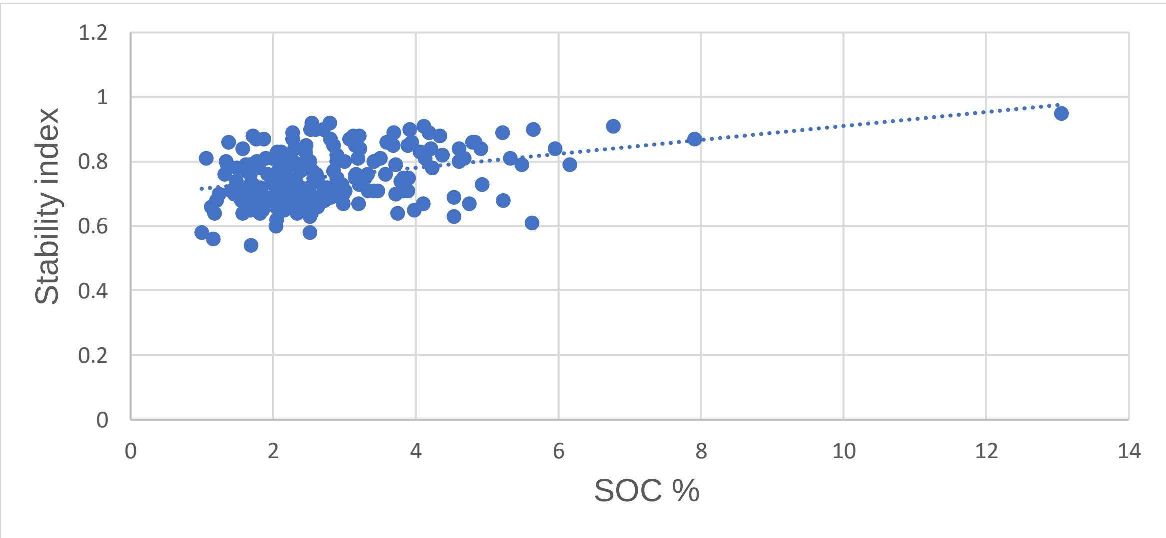

Figure A2: Relationship between SOC concentration and aggregate stability in arrange of soil types.

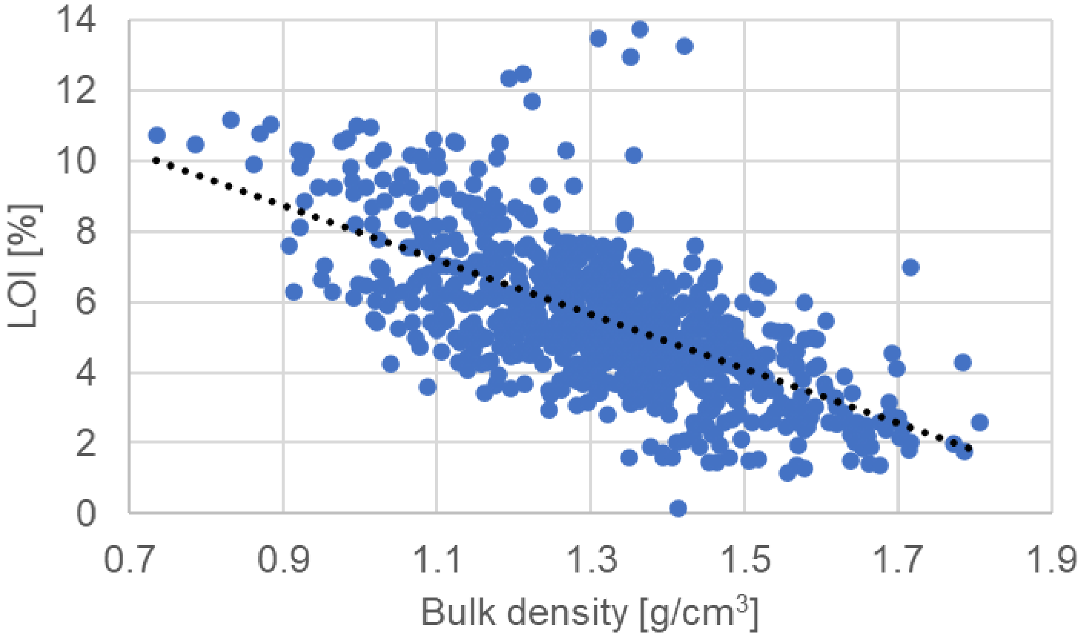

Figure A3: Relationship between loss on ignition (LoI) and bulk density from Soilbio dataset (Ken Loades)

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