Title:

Determination of organic carbon stocks in blanket peat soils in different condition - assessment of peat condition

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Final Project Report submitted to:

Scottish Environment Protection Agency

Submission Date:

30th of April 2015

Registered Office: Invergowrie, Dundee, DD2 5DA

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This document has been prepared in accordance with the requirements of the ISO 9001:2008 quality management system operated by The James Hutton Institute.

Approved for issue:

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Dated:

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1 Executive Summary

SEPA wished to commission this desk review in order to assess whether claims made in section 36 wind farm applications in relation to the condition, carbon stock and current emissions from proposed development sites can be substantiated. Such applications require use of the carbon calculator in order to estimate carbon losses from the peat as a consequence of wind farm construction. However, peatland condition is taken account of within the calculator. Within this report we assess the potential to classify peatland condition on blanket peat soils in Scotland and develop a protocol to determine resulting differences in carbon stocks and emissions in peat soils. We review existing classification systems and review the available datasets on carbon stock parameters, assessing how they might vary with condition.

We review the existing literature on peatland condition assessments, in particular in relation to the likely carbon stocks or emissions associated with different condition categories, building upon previous work and that within a current Defra-funded project on the UK Peatland Code. We had already completed a rough classification analysis of peatland condition for Scottish Natural Heritage and the Scottish Wildlife Trust. We are currently developing a spatially explicit index of peatland restoration suitability within the WISE Peatland Choices tool. More detailed information on peatland condition is included through, e.g., SNH's Site Condition Monitoring dataset for designated areas. We also have access to remotely sensed indicators through our analysis of MODIS products and review other remotely sensed datasets with potential to reveal site condition. We relate estimates of GHG emissions from the various observed peatland condition categories and assess what elements of current site condition monitoring may be useful for the purpose of characterising peatland condition and potential carbon emissions.

There remains an enormous challenge for the mapping of peatland condition. The extent of drainage, muirburn, active erosion and grazing-induced vegetation change are very difficult to quantify with existing mapped data and should be subject to more on the ground investigation. While some more refined estimates of the emissions of greenhouse gases from sites in different condition categories could be implemented in carbon calculations for future developments, the uncertainties in the figures remain large.

We consider the nature of peat soil condition in relation to soil carbon stock data and suggest a protocol based on that given within the recently developed Peatland Code. This ensures that peat condition can be assessed at a suitable scale to allow comparison with soil carbon stock data and which can be aligned with GHG emission factors. This protocol will provide the minimum data set for valid analysis of a site's potential for carbon losses (or gains) but at the same time is practical enough to be carried out by competent contractors. The aim is to not only estimate C stock but to broadly characterise current emissions

(positive or negative) along the lines of an IPCC Tier II emission factor methodology and to align it with the UK Peatland Code.

The addition of woodland (conifer or broadleaf), improved grassland, arable land and peat cuttings can extend the current four Peatland Code categories to cover most situations on the ground. The measurement of water table depth will provide useful additional information on condition. Since the Peatland Code was set up for carbon stock assessment, the additional parameters of peat depth and bulk density should be measured at a suitable intensity. The measurement of carbon content (%C) may be regarded as optional and recourse to default values should be satisfactory.

We also assess the relevant datasets for attributes that contribute to peat soil carbon stock (soil bulk density, carbon content, peat depth, peat area covered). These include the datasets that formed the basis of the ECOSSE II report. Additional data has been acquired during the National Soil Inventory of Scotland (NSIS) work though sampling in this was limited to the upper 100 cm of the soil or peat profile. Similarly, we report on data that was gathered during the Countryside Survey (CS; limited to the top 15 cm). We explore whole profile data that has been recently digitised and which formed part of the original Scottish Peat Surveys but has never been utilised.

From these datasets it is clear that blanket peats tend to have higher bulk density values than basin peats. This was borne out by both the NSIS data and that computed from the Peat Surveys. Unfortunately we were unable to gauge this from the CS data as this information was not specifically included. There is evidence that bulk density does not vary greatly with depth though deeper bogs tend to have overall smaller bulk density values. There is limited evidence on how peatland condition impacts bulk density. From the CS results, ‘priority’ blanket bog, which we presume to be in better condition, had a lower bulk density than non-‘priority’ bog. Vegetation classes (NVC classes) which indicated better condition (non-degraded) also showed lower bulk density values. It was clear from both the NSIS and CS data that replacement of bog vegetation with more grassland vegetation was accompanied by a marked increase in bulk density. From the Scottish Peat Surveys there was a trend for more intense drainage to be reflected in higher surface bulk density values. Carbon content values were much less variable than bulk density values. Values increased slightly with peat depth and degree of decomposition but did not differ between blanket and basin peats.

From this study it was clear that there are a number of gaps in knowledge which require addressing before we can satisfactorily describe how peatland condition may impact carbon stocks. To this end a number of recommendations for further research and data compilation are made.

2 Introduction

Recent years have witnessed a rapid expansion of wind farms throughout Scotland. As of September 2014, there were 572 windfarms developments of which 243 were operational and the remainder either under construction or approved. Approximately 33% of wind farm turbines are located on peat soils with 30% of developments of over 50 MW capacity (so-called "section 36" windfarms) on deep peat (> 1 m) (Waldron et al., 2015). The impact of developments on peat in terms of carbon balance depends, in part, on the initial condition of the peatland. Whether a peatland is actively sequestering carbon or is losing carbon through erosion or oxidation affects how developments are viewed. Additionally, we have little understanding of how current peatland condition may be reflected in the total carbon stock, as assessed from peat depth, bulk density and carbon content.

SEPA wished to commission this desk review in order to assess whether claims made in section 36 wind farm applications in relation to the condition, carbon stock and current emissions from proposed development sites can be substantiated.

Within this report we assess the potential to classify peatland condition on blanket peat soils in Scotland and develop a protocol to determine differences in carbon stocks and emissions in peat soils of differing condition. We review existing classification systems of peatland condition (e.g. NVC type, land cover class, CSM site condition, remote sensing based classification systems, and on-the-ground condition assessments as per the draft UK Peatland Code) and review the available datasets on carbon stock parameters, particularly focussing on bulk density.

3 Background

3.1 Use of the carbon calculator

Wind farm developments of over 50 MW that take place on, or partly on, peat soils require the use of the carbon calculator (Nayak et al., 2008; Nayak et al., 2010; Smith et al., 2011) as part of the planning process. The purpose of the calculator is to estimate the various carbon losses (in terms of carbon dioxide equivalents) incurred as a consequence of the construction of the wind farm and to compare this with the wind farm carbon emission savings. Some of these losses will be as a result of excavation and drainage of the peat resource if all or part of the wind farm is constructed on peatland. In some cases there may be carbon gains, where part of a development undergoes restoration. Critical to the calculation of the carbon losses is knowledge of the volume of peat involved, the weight of peat and consequently the weight of carbon. Input parameters are the area and depth of peat, the peat dry bulk density and the peat carbon content on a weight for weight basis. Within the model, the volume of peat affected is calculated from the drainage or excavation depths. Nevertheless the total depth of peat is also an input parameter as it will indicate the total quantity potentially at risk.

Users of the carbon calculator are expected, as far as possible, to input their own site-specific values for peat depth, peat dry bulk density and peat carbon content. While peat depth is relatively easy to determine in the field, measuring peat bulk density is more difficult requiring precise sampling of peat of known volume and access to laboratory facilities where samples can be dried and weighed. Determining carbon content is even harder requiring access to more expensive equipment such as an elemental analyser. Peat depth is likely to be very variable, even across a single site, varying with slope, underlying topology, hydrology, and position on the landscape in relation to the peat formation; it is essential therefore that it is determined on site in detail. There is a temptation for users to apply default values for either bulk density or carbon content or both and this is permitted on the calculator spreadsheet. Carbon content does not vary greatly in most Scottish peats and the use of a default value will not incur much loss of accuracy, particularly in comparison with the uncertainties in other parameters within the calculator. However, dry bulk density can be quite variable; possible values may range from 0.04 to 0.34 g cm^{-3}, potentially resulting in an eightfold change in the calculation of peat weight. Also dry bulk density may vary with depth, typically being greater at the surface and decreasing lower down the profile in more degraded peats (Frogbrook et al., 2009) but being lesser at the surface and increasing with increasing depth in more pristine peats (see, e.g., Lindsay, 2010). Some of these aspects have been discussed in detail in the context of estimating peatland carbon stocks across the country (Chapman et al., 2009; Smith et al., 2009; Smith et al., 2007).This variability in bulk density is a complication which the carbon calculator does not take into account; however it does relate to peatland condition.

The carbon calculator has been specifically designed for wind farm installations. Currently it is used primarily for developments over 50 MW but equally it could be (and has been) used for smaller developments. However, the principles and methodology could equally be applied to other significant developments on peat soils such as hydroelectric schemes, road infrastructure or urban expansion, though this would require a complete revision of the current calculator.

3.2 Peatland condition

Peatland condition is not entered into the carbon calculator. There is no consideration of vegetation type or cover, except for those areas under forest where some parameters reflecting the type of forest and its stage of growth are required. Average water table depth is required but not as a condition indicator per se. However, it could be applied as a very useful proxy.

Where peat is claimed to be 'damaged', 'degraded' or 'eroded', it is reasonable to suggest that carbon losses following development will be less than those incurred on sites in better condition but this is a qualitative assessment that has not been quantitatively evaluated. Currently we have a poor understanding of the impacts of 'condition' on such parameters as peat depth, dry bulk density and carbon content. We have some very limited information on effects of erosion on peat depth but the degree of erosion is poorly characterised (Smith et al., 2007). Condition may also impact on current carbon emissions and the possible alteration of future carbon emissions following any development, i.e. on a weight for weight basis, already degraded peat may produce lower emissions than pristine peat following installation of a wind farm. However, a full life cycle analysis should always be carried out and emissions following development compared with emissions following restoration. It has been suggested that wind farms on undegraded peatlands are unlikely to reduce carbon emissions (Smith et al., 2014).

Current assessments of peatland condition are primarily focussed on vegetation and physical condition, though in some surveys both flora and fauna may be considered. Hence this is a literally superficial assessment and the condition of the underlying peat soil is not taken into account. An exception is where water table or drainage status is recorded. However water table is difficult to assess on one-off surveys as it will vary considerably with both season and antecedent weather. It is important to recognise that carbon stock depends on the prior conditions during peatland development (vegetation/hydrology) and any previous management, which may not be reflected at all by present management or vegetation. There is an element of history here, i.e. to what extent (or depth) has recent management altered the C stock? Erosion may be very long-lived, drainage may be shallow or deep, and management interventions may be recent or historic. In assessing condition, most current practice and experience has been in assessing areas designated for nature conservation purposes and so have been biased towards those peatlands in better condition. Developing a methodology for assessing peatland in a wider range of conditions will require a protocol that can cover all types of blanket peat condition and that will assess the peat soil rather than just the peat vegetation. Clearly we need a methodology that is straightforward enough to be readily applied by developers/contractors and robust enough to cover the multitude of conditions that may be encountered but which goes beyond the current broad estimation of peat depth.

Combining carbon stocks data and peat soil condition will tell us how much carbon stored in peatlands is at risk and will help to project current and future (disturbed) emission rates. Peat depth will always be needed for stock estimates but peat condition may potentially give an indication of bulk density and carbon content if these values are not directly available, and would be preferable to using default values.

4 Objectives

The principal objectives of the project were:

Objective 1: Outline the adaptations/changes that would need to be made to existing systems of peatland condition classification to enable assessment of peat soil condition at locations where measurements of soil carbon stocks are made.

Objective 2: Develop a protocol for assessing the condition of peat soil that is suitable for establishing peat soil condition at locations where measurements of soil carbon stocks are made, outlining methodology for this protocol in full.

Objective 3: Perform an assessment of existing Scottish soil bulk density data, depth and percentage carbon data and consider how suitable this data is for determining carbon stock in peat in different condition. Particular reference should be made to the outcomes of the ECOSSE II project and considerations given to ways of building on these.

5 Results

5.1 Objective 1:

5.1.1 Outline

Here we review the existing literature on peatland condition assessments, in particular in relation to the likely carbon stocks or emissions associated with different condition categories, building upon previous work (Artz et al., 2014a; Artz et al., 2014b; Artz et al., 2012a; Artz et al., 2012c; Chapman et al., 2012) and that within a current Defra-funded project on the UK Peatland Code. We have already completed a rough classification analysis for recently completed desk based reviews on blanket bog condition for Scottish Natural Heritage (Artz et al., 2012a), as well as for lowland raised bogs for the Scottish Wildlife Trust (Artz et al., 2012b). We are currently developing a spatially explicit index of peatland restoration suitability within the WISE Peatland Choices tool. More detailed information on peatland condition is included through, e.g., SNH's Site Condition Monitoring dataset for designated areas. We also have access to remotely sensed indicators of site condition through our in-house analysis of the 500 m MODIS products (2000-present) and review other remotely sensed datasets with potential to reveal site condition. We relate estimates of GHG emissions from the various observed peatland condition categories. We assess what elements of current site condition monitoring may be useful for the purpose of characterising peatland condition and potential carbon emissions.

5.1.2 Peatland GHG emissions

There are a number of both international and national drivers leading to the production of assessments of GHG emissions from UK peatlands in different condition categories. First and foremost, the publication of the 2013 IPCC Wetlands Supplement (IPCC, 2014) has paved the way for the sub-classification of any peatland that has been drained and converted in land use. The condition categories at the lowest Tier of reporting (Tier 1), however, do not map very well onto UK peatland condition categories and furthermore, the GHG emissions averages assigned to the Tier 1 categories encompass peatlands in all temperate areas. For these reasons, various working groups have suggested that the UK should develop higher Tier reporting categories, inclusive of their own carbon metrics. At present, much of this work is still in progress.

The Department of Energy and Climate Change (DECC) , in response to the publication of the 2013 IPCC Wetlands Supplement, have commissioned a project running to April 2016 to produce a review of the requirements for implementation of the new protocols, and to develop UK-specific GHG emissions factors for the appropriate peatland condition categories observed in the UK. The project team have submitted two interim reports to date, which give first indications of the likely condition categories that will be used. Along very similar lines, the Peatland Code working group have been reviewing the available evidence to develop a field-applicable protocol for peatland condition as part of a Defra funded project (Project NR0165). In tandem with the field protocol, data on GHG emissions have been collated and summary statistics produced in order to develop a standardised carbon metric methodology and associated protocols for the Peatland Code. At present still in draft form (Smyth et al., 2014), the standardised Peatland Code metric uses four peatland condition categories: near natural, modified, artificially drained and actively eroding. These have been tested in the field and with different user groups and seem to be generally well accepted (Smyth et al., 2014). The final report for this project was due March 2015. In addition, the

DECC project working group is also including the more heavily modified condition categories of Forest cover (split into broadleaf and conifer), Improved grassland, Cropland, Peat extraction and Rewetted sites, in order to comply with the land use categories required for National GHG Inventory Reporting under LULUCF and Kyoto Protocol guidelines.

The emission factor calculations for each of these condition categories used a subset of the publications cited in the 2013 IPCC Wetlands Supplement, where these were relevant to UK peatland types and climatic conditions, and augmented these with additional data where there had been more recent publications. The final dataset was quite limited in terms of the data deemed relevant to the UK situation, with many of the GHG pools showing insufficient data for a statistically robust estimation of the likely flux.

Table 1 shows the current status of the analysis, with indicative average figures for the GHG emissions from each of the proposed condition categories. However, it must be pointed out that there are very wide error margins associated with these figures, as illustrated in Figure 1 for the less damaged categories. All condition categories with the exception of near natural sites are, on average, net CO_2 sources, with very few studies indicating net CO_2 sequestration in disturbed peatlands. All of the near natural sites are net CO_2 sequestering. This net uptake of carbon dioxide is partially offset by methane emissions. In near-natural sites, the average methane emissions appear to be large enough to cancel out the average carbon dioxide uptake. However, it is worth bearing in mind that this would not be a valid conclusion to make, as a partially different set of sites, years, and treatments contribute to the calculated average methane emissions compared to those used for the carbon dioxide averages. Ideally, full carbon budgets should be compiled at the individual site level and then combined at the condition category level. However, this is not feasible at present as many studies only focus on a single greenhouse gas. The available data for nitrous oxide fluxes are particularly scarce and Smyth et al. (2014) concluded that the emissions averages across all assessed condition categories are not robust enough to be included in formal carbon accreditation. Hence, it was suggested that emissions from nitrous oxide fluxes should be estimated at zero, until further UK data become available. These interim emissions data could be used to more accurately estimate the likely losses of carbon from the site in the case of development, if the Carbon Calculator for wind farms were to be adapted to take into account the site condition of the peatland under the proposed development.

Table 1. Emission factors (EF) used for assessment, with data sources Peatland Code (Smyth et al., 2014) and IPCC Tier I (Evans et al., 2014b). Emission factors for DOC and POC represent the estimated CO_2 emission associated with waterborne loss of these carbon forms into drainage networks (IPCC, 2014). Negative values indicate that the peatland is a net sink. Values in parenthesis indicate the standard error.

Category	EF (CO_2)	EF (POC)	EF (DOC)	EF (CH_4)	EF (N_2O)	Total GHG	Source
	t CO_2-eq ha^{-1} y^{-1}						
Bog (near natural)	-3.0(0.7)	0	0.88	3.2(1.2)	0	1.08	Peatland Code
Bog (modified)*	-0.1(2.3)	0	1.14	1(0.6)	0.5(0.3)	2.54	Peatland Code
Bog (drained)	1.4(1.8)	0	1.14	2.0(0.8)	0	4.54	Peatland Code
Bog (eroding)	2.6(2.0)	19.3	1.14	0.8(0.4)	0	23.84	Peatland Code
Woodland (conifer)	9.53	0	1.14	0.33	0.53	11.53	IPCC Tier 1
Woodland (broadleaf)	9.53	0	1.14	0.33	0.53	11.53	IPCC Tier 1
Improved grassland	17.78	0	1.14	1.71	0.93	21.56	IPCC Tier 1
Cropland	28.97	0	1.14	1.46	2.47	34.02	IPCC Tier 1
Fen (near natural)	1.83	0	0.69	4.05	0	6.58	IPCC Tier 1
Peat extraction	10.27	5.27	1.14	0.82	0.06	31.59	IPCC Tier 1
Rewetted bog	-1.2	0	0.69	4.10	0	3.59	Peatland Code
Rewetted fen	1.83	0	0.69	4.05	0	6.58	IPCC Tier 1

*modified by current or past burning, over-grazing or pollution

5.1.3 Problems of mapping peatland condition

While it is possible to produce simple map overlays of some of these land cover categories onto soil maps in order to produce maps of peat condition categories, there are some complicating factors that mean such mapping work would result in erratic allocations. At present, the data required to map Scottish peatlands into these condition categories (Table 1) are incomplete or need to be seen in the context of a number of important caveats. The DECC project team (Evans et al., 2014b) reiterates these concerns and made a number of assumptions in order to produce a reasonably complete set of land cover estimates for each condition category. For Scotland, an important caveat of the peat soil maps is that these include mapping units where peat occupies some but not all of the area, but where the exact location of the peat is not mapped separately and instead is estimated as a percentage of the overall map unit. This leads to considerable uncertainty when overlaying land-use/condition data on the peat map. A comparison of Scottish land cover maps and high resolution aerial photography data (GetMapping 25 cm resolution data from 2008-2013) highlights large discrepancies in classifications at the local level.

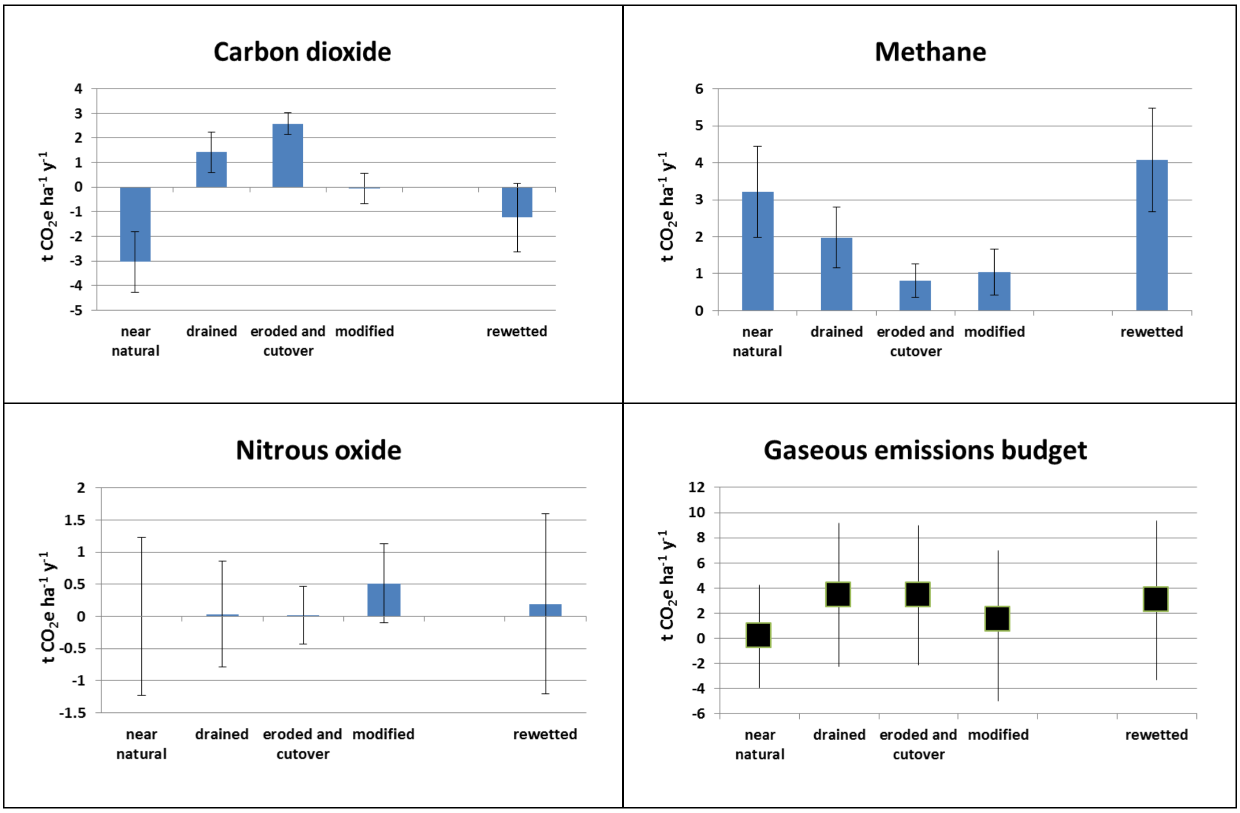

Figure 1. Examples of the range of GHG emissions from the less damaged categories of UK blanket bogs, by condition category (modified from Smyth et al., 2014).

The condition of peatland sites in Scotland was estimated using a combination of the Land Cover of Scotland 1988 dataset (LCS88; Macaulay Land Use Research Institute, 1993), the Land Cover Map 2007 (LCM2007, Centre for Ecology and Hydrology, 2011) and data from Forestry Commission Scotland's holdings. These were intersected with a combined peat map for Scotland, which included data from the 1:25,000 Soil Map coverage of Scotland where data were available, augmented with data from the 1:250,000 National Soil Map of Scotland (Macaulay Land Use Research Institute, 1982). The resulting draft condition category maps were manually spot checked for accuracy by visualising several random polygons within each category at high resolution and visual inspection against the most recent aerial image data from GetMapping.

The mapped areas of the draft 'good condition' (near natural bog) category, using either the LCS88 or the LCM2007 datasets, showed very different suggested locations depending on the land cover map used. The LCM2007 generally comprises larger polygons that would contain more than one condition category in the LCS88. For example, a large number of LCM2007 polygons mapped as near-natural bog included areas recorded as forestry (see example in Figure 2) or showing erosion features in the LCS88 dataset, many of which were also visible in the GetMapping imagery. Hence the LCM2007 may over-estimate near-natural bog and under-represent erosion (LCM2007 does not include an eroded category, and the closest equivalent 'bare soil' category only captures very small areas on peat). The National Vegetation Classification (NVC, Averis et al., 2004) data are not available at present as a polygon layer. A download is available from the JNCC website (http://jncc.defra.gov.uk/files/Upland%20NVC%20types%20mapping%20tool%20(version%202).zip), however this dataset is presented only as point data for UK grid cells. Hence, at local level, the information presented would not be accurate and hence a scoping exercise could not be attempted with this dataset. The dataset includes 38 mire communities and 22 heath communities across the UK, which could theoretically provide some indications of the condition status of a peatland (see Appendix). However, in addition to not being spatially explicit at the local level, this dataset does not cover the total extent of peatland sites across Scotland (as we indicated in the original tender) and is thus not immediately applicable to a peatland condition mapping exercise across the whole of Scotland.

Figure 2. LCM2007 overlay of 'bog' (yellow) habitat includes areas of forestry, some of which are undergoing felling (i.e. restoration) at present.

5.1.4 Peatland drainage

Similarly, the LCS88, whilst mapping some land cover features better than the LCM2007, is unable to distinguish near natural from drained bog (see example in Figure 3) as drainage grips have never been mapped in Scotland. For the DECC project, the area of drained peatland was based on an assumption that 25% of all peatlands were drained. On individual sites, therefore, such information would have to be provided by the land owner/manager. Mapping of drains could be attempted at national scale and Artz et al. (2012a) showed examples of automated image analysis which has provided estimates of drainage locations and density at the local scale in the Flow Country. However, completing a peatland drainage map for Scotland is not a small task. While open grips can often be relatively easy to recognise on aerial images (Figure 3), there will be areas where the grips have started to grow over in the absence of any management.

As part of some scoping work carried out in 2013, the location of drainage channels identified from aerial images on the island of Yell (Shetland Islands) were ground-truthed by fieldwork staff and students. It became clear that such older drainage grips are often difficult to distinguish from older, unmaintained, fencing, and that evidence needs to be provided that such grips are still functioning (i.e. transporting water off the hill). In some cases, it is difficult to ascertain whether an erosion gully started out naturally, or, as in the case in Figure 4, may have been formed as a consequence of erosion of a drainage channel.

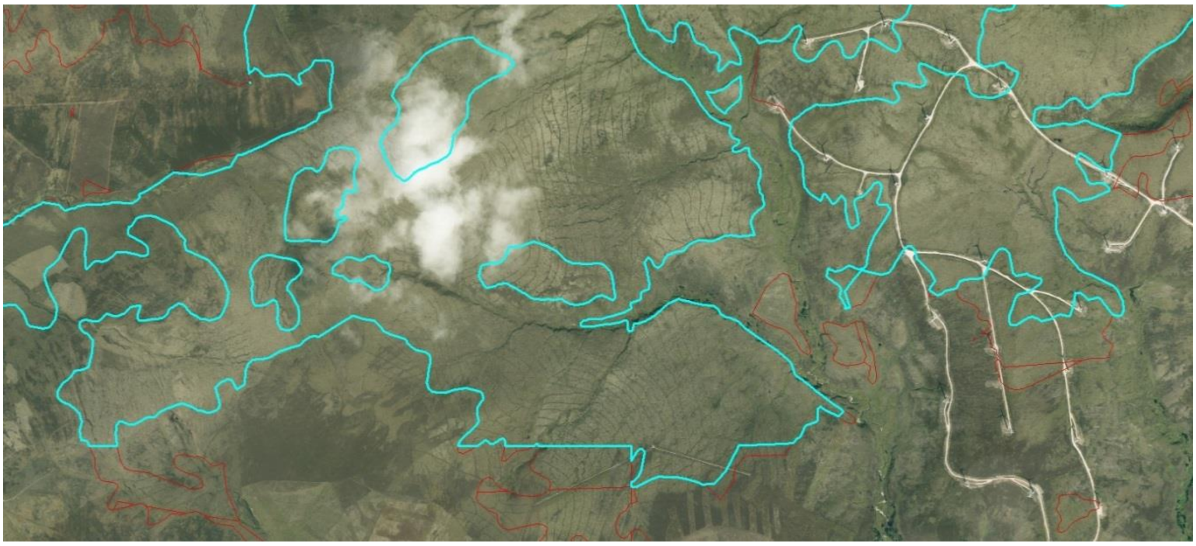

Figure 3. Large area (>1000 ha) of clearly drained bog, classified as 'blanket bog, no erosion, no trees' in LCS88. See also the new windfarm installed in this area.

A further challenge is the identification of the extent to which drainage channels affect the condition of the peatland overall. At present, the windfarm calculator makes an assumption that 10 m adjacent to a drain is adversely affected, and results in higher GHG emissions. However, this figure is not universally accepted, with several reports in the recent literature that report drainage effects on the water table in peatlands in excess of 10 m and in some cases, 25 metres (Armstrong et al., 2010; Holden et al., 2011; Wallage and Holden, 2011; Wilson et al., 2010). The carbon calculator for windfarm developments currently assumes that the extent of the influence of drainage features will be verified on the ground. Available aerial photography such as GetMapping does not provide enough contrast between areas adjacent to drainage channels and areas further away to be of use in the estimation of the extent of the drainage effect on vegetation.

A similar issue emerges with the mapping of the modified category (heather moorlands, grass-dominated wet heathlands and similar surface vegetation), in that the LCS88 and LCM2007-based estimates return different areas, both in terms of location and total areal extent. In particular, LCM2007 seems to have a different protocol for allocating moorland cover. In the example in Figure 5, an area that is classified in LCM2007 as bog is to some extent classified as modified (dry or wet heather moorland) or even as eroded bog in LCS88.

Figure 4. Overgrown drainage grips can be hard to distinguish, but may still be functional. The drains at a site on Yell (Shetland Islands) marked WP113-121 (blue lines) in the images above were still transporting water downhill and into an eroded channel which terminates in a culvert under the main road. The erosion channels possibly started as hill grips. However, fence lines (green) can show as very similar features in the imagery. Top image with fence lines and grips drawn in, lower image GetMapping original image.

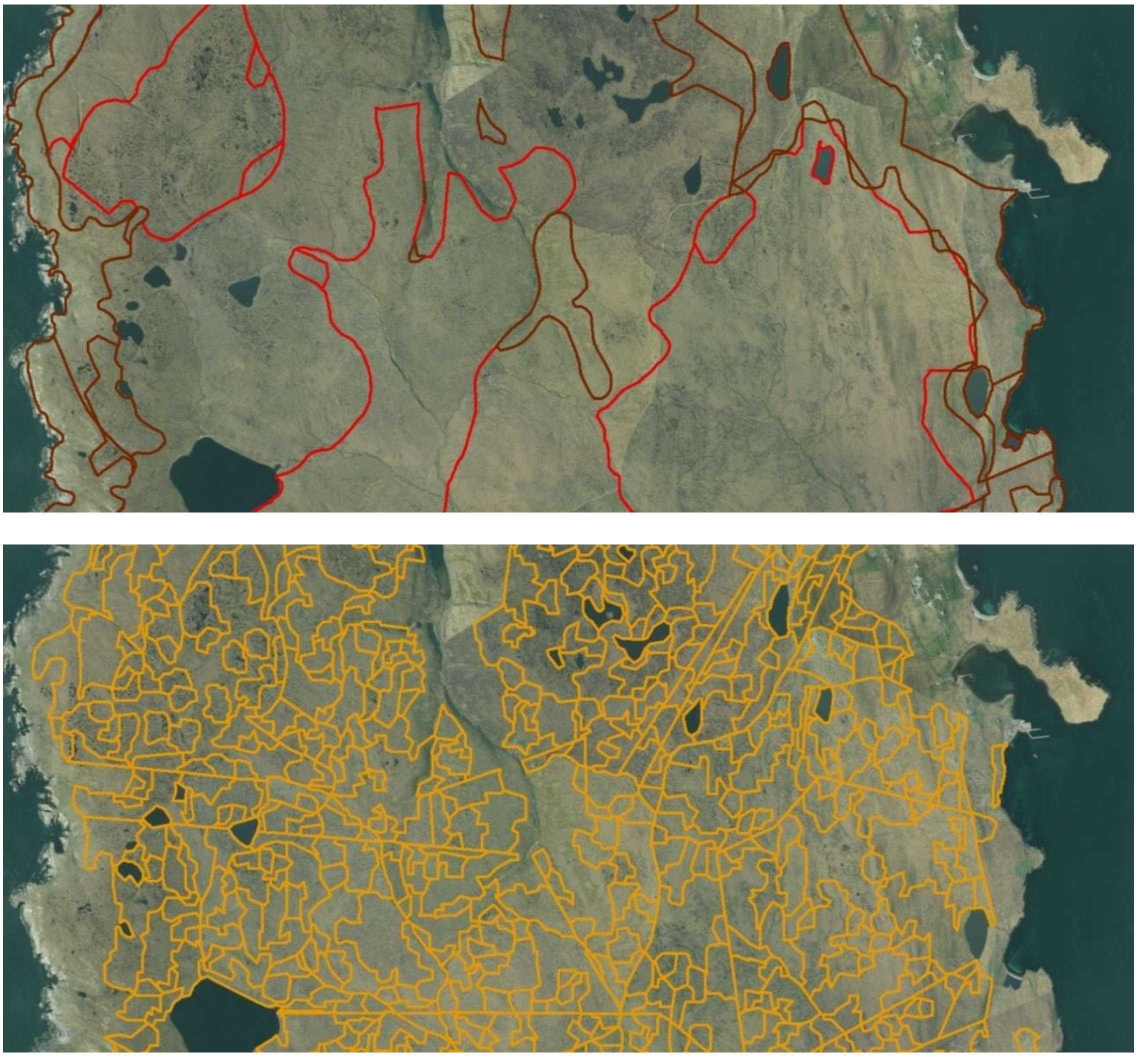

Figure 5. The same area shown with the LCS88 (upper image) classification into bog (red) and dry/wet heather moorland (brown) and with the LCM2007 classification of ‘bog (yellow). The entire area under the LCM2007 classification is almost universally ‘bog’, however this clearly groups eroding (top middle of the image are eroding bog under LCS88), good condition and drier surfaces together.

5.1.5 Peatland burning

Muirburn is even less identifiable in the currently available data sources. The LCM2007 does not include any features relating to muirburn at all, whereas the data in the LCS88 identify areas where burn scars were visible in 1988 imagery. Hence, overlays of the LCS88 polygons that contain burning as a feature can only be indicative of areas that would have been burned in the up to 10-20 years preceding 1988. There is also no comprehensive collation of data on the area of burning on moorland and degraded blanket bog. Evans et al. (2014a) summarise the situation as follows: “The Fire and Rescue service holds data on the area of wildfires which have required attendance of a fire engine to bring under control; SNH, Natural England, Welsh Government and DARD hold data on managed burns which have been licensed to take place under conditions which do not meet standard regulations, and areas of burn associated with some CAP Pillar 2 agri-environment schemes may be recorded, but these datasets do not provide comprehensive coverage of the area of burnt moorland. Although some remote sensing approaches to assessing burnt area have been piloted, none has been used across the UK or even right across a single administration”. Some promising attempts have been made by RSPB staff to classify muirburn in a categorical manner by manually scoring the percentage of heather burning in 1 km grid cells from GetMapping aerial image data across Scotland, however this work is as yet unpublished (Douglas et al., 2015). It should theoretically be possible to identify burn scars in the GetMapping 25 cm resolution data using more automated measures, with the caveat that an area identified as burnt may have been burned several years before the images were taken. Only in areas where data have been acquired over several years would it be possible to pinpoint roughly when the burn event has occurred (Figure 6). It is unknown at which point old muirburn scars have recovered to the extent where there is no recognisable difference with unburned areas in aerial imagery. A more refined approach to identifying areas of muirburn could potentially utilise the information held in some satellite-derived data. We scoped out a potential 50 km square where we held old LCS88 information on muirburn as well as GetMapping images (Figure 7). As the GetMapping data are a compilation of at least 6 years, with only small areas of overlap, it would be very difficult to ascertain the area of muirburn from such high resolution imagery.

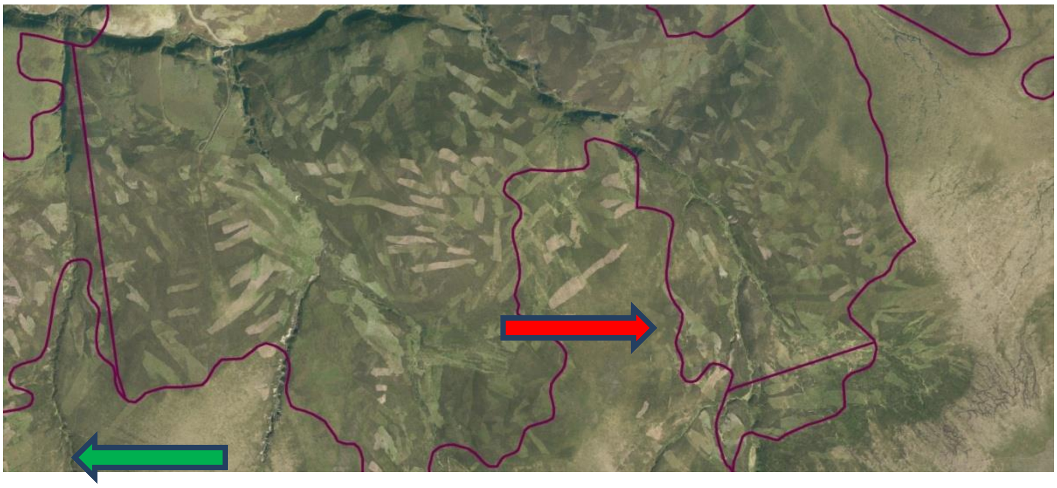

Figure 6. GetMapping images of an area where burning must have occurred in between the two different years of data acquisition. The top image was taken in 2010 (precise timing unknown) and the lower image in 2013. The purple line indicates an area where muirburn occurred on a polygon containing peat in 1988 (LCS88 overlay onto unified peat map). Within the purple areas, several new burns between 2010 and 2013 (example: red arrow) as well as recovering areas (green arrow) can be observed.

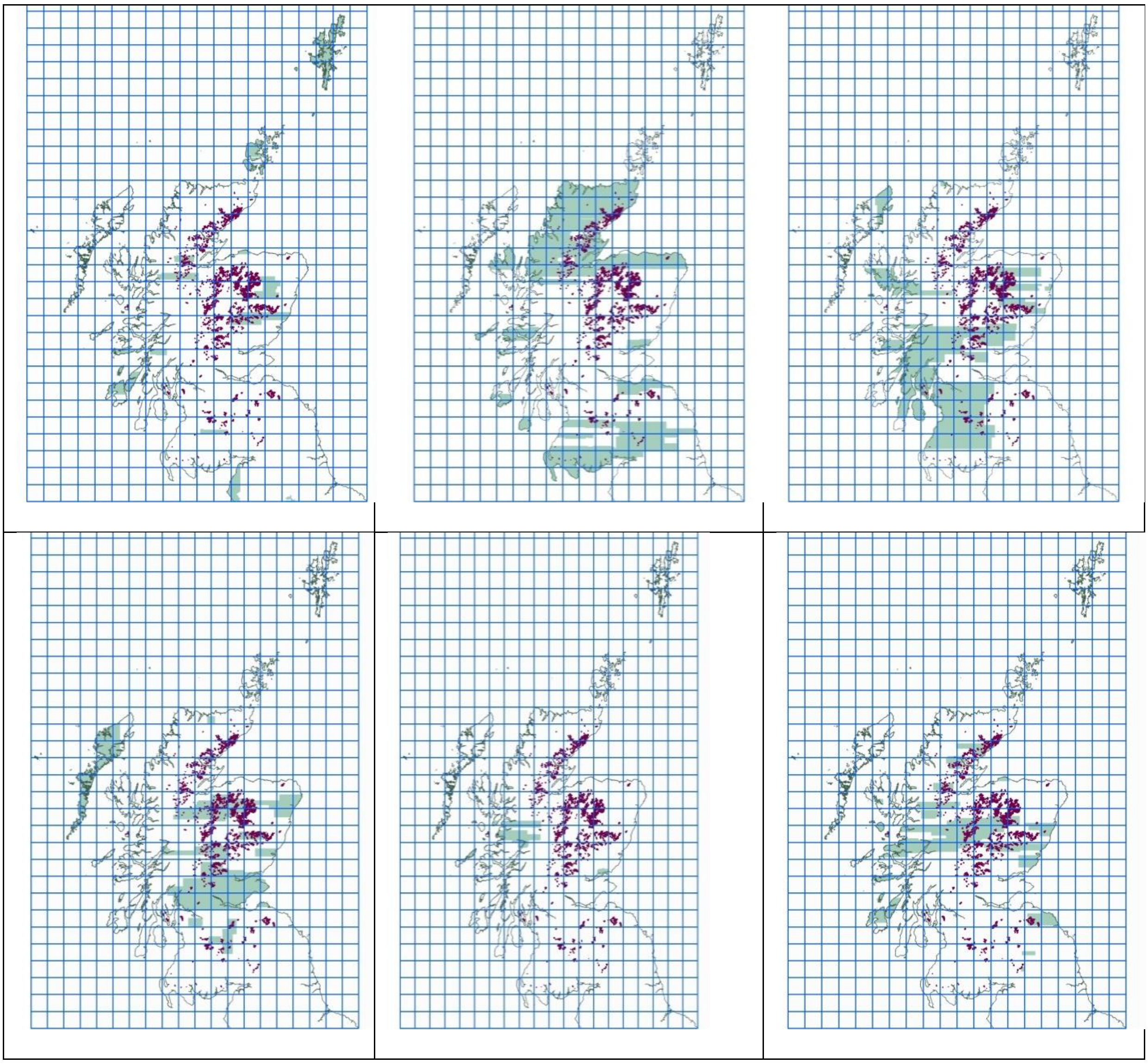

Figure 7. Distribution of aerial image data at 25 cm resolution. From top left: 2008, 2009 – 2013. Green areas indicate coverage of GetMapping data for that year. Purple are LCS88 areas with muirburn on wet dry heathland vegetation that overlap onto 1:250,000 polygons containing peat.

MODIS burn scar data are provided at a spatial resolution of 500 meters and attributed with the approximate day of burning on a per pixel basis. There are two possible algorithms to be used: NASA MODIS fire product (Christopher Justice et al., 2006) and the automated hybrid algorithm described by Giglio et al. (2009). Both burn scar science processing algorithms are utilized operationally within the direct readout processing framework managed by the USDA Forest Service Active Fire Mapping Program.

The MODIS burn scar algorithms takes as input composite datasets derived from daily Terra and Aqua MODIS observations. The algorithm conducts time series analyses on vegetation index data, derived from composited reflectance data, in the context of active fire detections to identify areas of change due to fire.

The derived products were examined in Scotland for year 2011 (Figure 8). This method does not seem to detect the burnt areas in Scottish moorlands. This is possibly a spatial resolution problem (pixels are 500 x 500 m). In the chosen year only unburnt areas could be identified as most of the areas most likely to be burnt (see analysis with aerial images) were covered in snow or clouds during the burning season. This is often the case with MODIS summary products (e.g. monthly composite dataset as the one used in this explorative study). A detailed temporal analysis of daily or weekly data and the use of more years might improve the results and provide more insight in the use of MODIS for burn scars detection in peatlands. However, it is more likely that burn scars can be detected by applying the same algorithm to the new SENTINEL satellites. These will have an overpass frequency of a few days and give high resolution products (10–20 m).

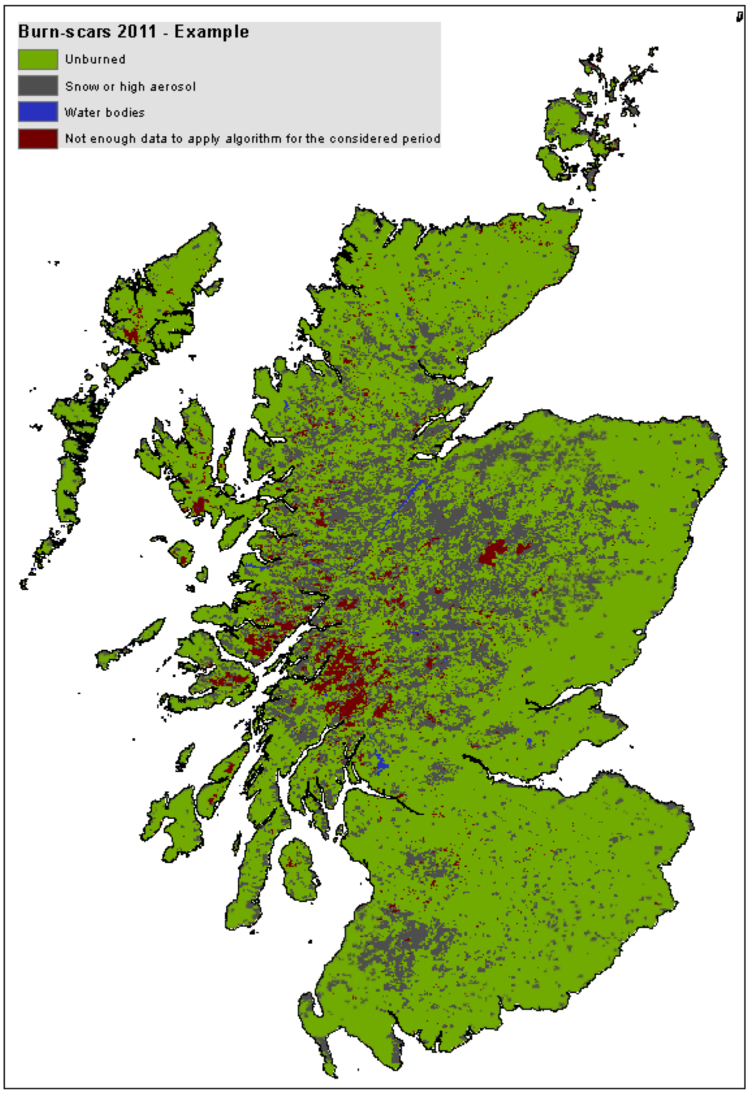

Figure 8. Failed preliminary attempt to reveal burnt areas from MODIS imagery

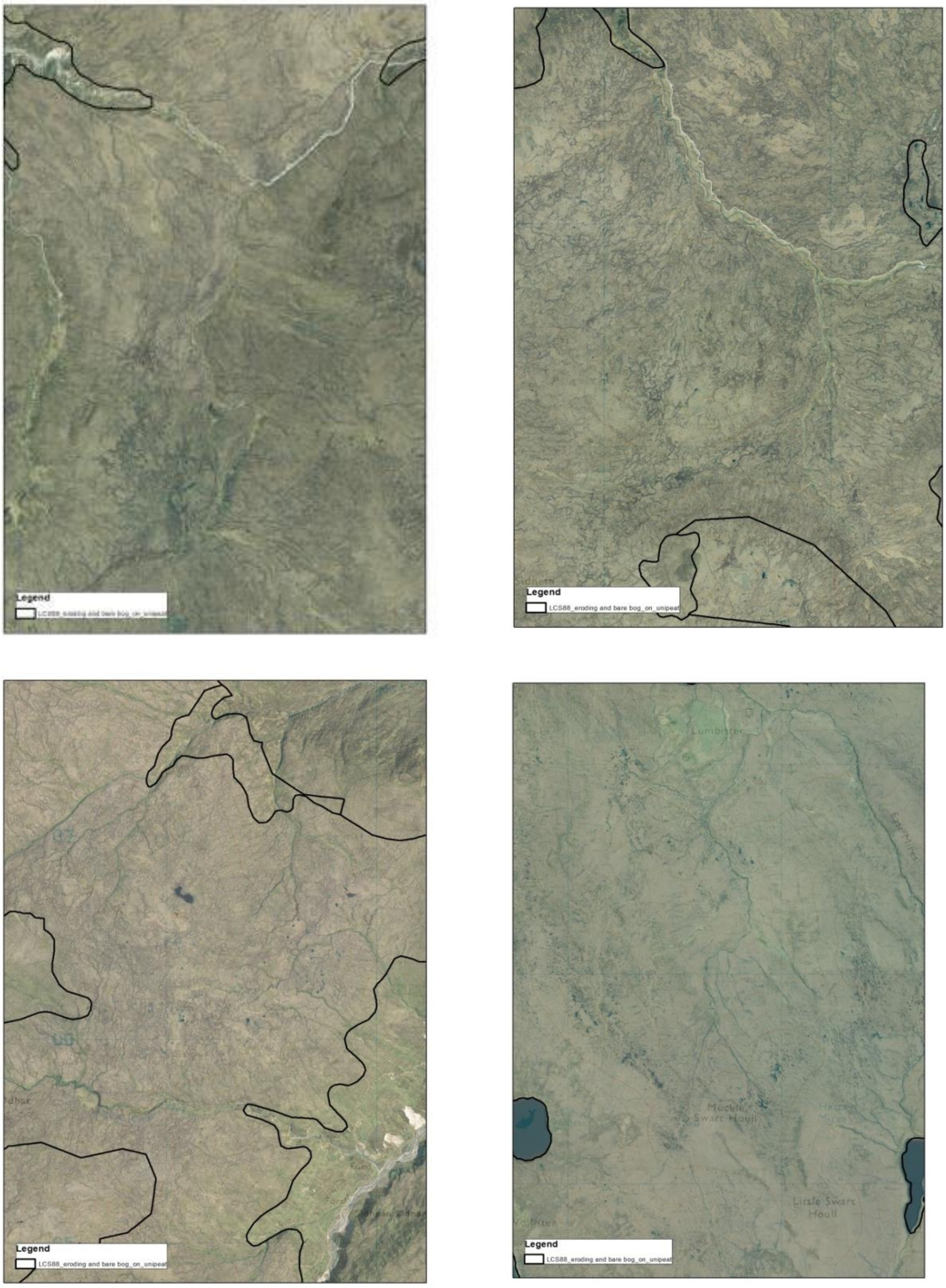

Figure 9. Examples of LCS88 map overlays of erosion-containing LSC88 polygons (>100 ha, black lines indicate outer boundaries of erosion feature containing polygons) onto GetMapping aerial images at ca. 1:10,000. The actual on-the-ground coverage of the erosion features can vary between 5 and 50% of the total area, with upper images showing examples of more extensive erosion and lower images of less extensive features.

5.1.6 Peatland erosion

As a final condition category for which data sources are unlikely to be adequate at present, we investigated eroded peatlands. Erosion in the LCS88 was identified as single entity polygons and as either dominant or subdominant features within a mosaic polygon. No records, however, were kept of relative importance (extent, intermixture) of each feature beyond the dominant/sub-dominant distinction. In addition, where mosaics with more than two features occur, only the two most dominant are recognised (i.e. this would probably mean that there is a bias against microerosion). A visual assessment of a small subset of these polygons using aerial photo data indicated that the actual erosion features can occupy a very variable amount of the total ground area (Figure 9). As a first estimate, a very approximate figure of 25% of the total area, of which approximately half the area was thought to show active erosion, was used in Evans et al. (2014b).

5.1.7 Conclusions

There remains an enormous challenge for the mapping of peatland condition, especially in areas remaining under semi-natural vegetation. In particular the extent of drainage, muirburn, active erosion and grazing-induced vegetation change are very difficult to quantify with existing mapped data and should be subject to more on the ground investigation. We have therefore refrained from producing any maps at national scale of peatland condition categories, as these would be visually misleading. While some more refined estimates of the emissions of greenhouse gases from sites in different condition categories could be implemented in carbon calculations for future developments, the uncertainties in the figures remain large and would thus also need to be taken into consideration. Assessment of peatland condition category could take place on the ground, using the Peatland Code field protocol (Smyth et al., 2014) and should be mapped in a similar manner to the current Phase 1 habitat surveys and/or NVC classification surveys carried out as part of any planned development. Additional data should include the location of any drains, erosion features and muirburn, and a protocol for the assessment of the extent of drainage effects should be developed. For example, monitoring of water table fluctuations along a transect from a drain would provide useful data for modelling purposes if carried out at a reasonable number of sites across Scotland and such data would be invaluable in updating the default values in the carbon calculator.

5.2 Objective 2:

5.2.1 Outline

Here we consider the nature of peat soil condition in relation to soil carbon stock data and suggest a protocol that ensures that peat condition can be assessed at a suitable scale to allow comparison with soil carbon stock data and which can be aligned with generalised GHG emission factors. The protocol will provide the minimum data set for valid analysis of a site's potential for carbon losses (or gains) but at the same time is practical enough to be carried out by competent contractors without undue cost or delay, reliance on sophisticated equipment or recourse to information/data that is not readily available. The aim is to not only estimate C stock but to broadly characterise current emissions (positive or negative) along the lines of an IPCC Tier II emission factor methodology and to align it with the UK Peatland Code.

5.2.2 Assessing site condition using the Peatland Code

"The Peatland Code is the voluntary standard for peatland restoration projects in the UK that want to be sponsored on the basis of their climate and other benefits."[1] One of the code's objectives is to assess site condition and relate it to likely GHG emissions so that sponsors can obtain some measure of the carbon benefits from restoration. This is currently under development and shortly to be published (Taylor et al., 2015). These objectives align closely with those of the current project where a relationship between peatland condition and likely emissions is sought for sites that may be subject to either restoration or development. It is therefore put forward as a possible avenue for fulfilling objective 2, at least in part. Even if not accepted in its entirety, there are elements of the field assessment methodology that could be usefully adopted. There are advantages in using the Peatland Code methodology:

- There are clear benefits in having a more unified system of condition assessment, especially where the alternatives of restoration or site development are being considered.
- The methodology is fairly low key and does not require specialist skills.
- Peat depthing is included. However, this is only to check the depth exceeds 40 cm (England and Wales limit for peat definition); this would need to be extended to a full depth measurement.

[1] http://www.iucn-uk-peatlandprogramme.org/peatland-gateway/uk/peatland-code

- Condition assessment categories can be linked to emission factors (see Table 1).

For the complete protocol the “Peatland Code. Assessing the condition of your project site: Guidance and Procedures” document should be consulted (Taylor et al., 2015). Here we give a brief outline:

1. Using Google Earth or other aerial imagery, produce a base map of the area under consideration.
2. Mark out areas that can be seen to be either eroded or drained. Drainage ditches are assumed to impact an area 30 m away from the outer ditch. Remaining areas are taken to be either ‘near-natural’ or ‘modified’; distinguishing these two categories will require field examination (Table 2). These areas form the ‘Assessment Units’ for field survey. The number of units should be the minimum achievable.
3. Map the Assessment Units and calculate their area.
4. Conduct a field survey. This is facilitated by using a prepared standard form (tick sheet), which if followed will confirm the assessment categories.
5. The surveyor takes a zig-zag (or ‘N’-shaped) line across each assessment unit. Along each straight leg three peat depth measurements are made and again at the turning point. Here a condition assessment is made, filling in the tick sheet. This is repeated so that for each Assessment Unit there will be a total of 12 peat depth measurements and three condition assessments (Figure 10).
6. Each condition assessment identifies the presence of eroding hags or gullies, extensive or patches of bare peat, drains within 30 m, presence of *Sphagnum*, evidence of burning and evidence of grazing and trampling.
7. On the basis of these observations, the condition category is confirmed.
8. Based upon the area and the relevant emission factor (Table 1), the total emission can be estimated as well as the carbon gains from restoration if the end state can also be predicted. This would generally be near-natural but in some cases only a modified or even drained state may be reached.

Table 2. Condition categories as used in the Peatland Code. After Taylor et al. (2015).

Condition Category: Drained Indicator: drains (not natural watercourses) present. Some of the categories are easier to identify using aerial photography than others. Drains can show as obvious linear features, both in an apparently random arrangement and in a more uniform parallel layout. Drained areas are to be mapped as discrete Assessment Units, with the mapping unit measured as 30 m out from the edge of the last drain. This gives the estimated area that has been drained, and subsequently the area that can be expected to be re-wetted following restoration.
Condition Category: Actively Eroding Indicators: presence of actively eroding haggs/gullies with no or limited vegetation in gully bottoms and/or areas of extensive continuous bare peat. In severe cases where bare peat is extensive, actively eroding peat can be very obvious, appearing as dark broken edged areas on aerial photographs. Often a hagg and gully landscape is identifiable although there may not be bare peat visible. This could indicate limited active erosion or historical erosion (subsequently re-vegetated). These areas should be mapped as an Assessment Unit so the field survey can determine if the areas meet the criteria of the Actively Eroding category or the Modified category.
Condition Categories: Near Natural and Modified Indicators: areas which appear to be peat but are not drained or actively eroding, obviously managed (e.g. burn areas clearly visible), areas of historical peat loss now re-vegetated (no bare peat). These categories are the hardest to distinguish from aerial photographs but are usually mapped as areas which do not fit the criteria for Drained or Actively Eroding Condition Categories. Usually some understanding of current and past management will help determine if the areas are likely to be Near Natural or Modified. Some features are very distinctive, such as burning, but it is generally assumed that these categories are best distinguished in the field.

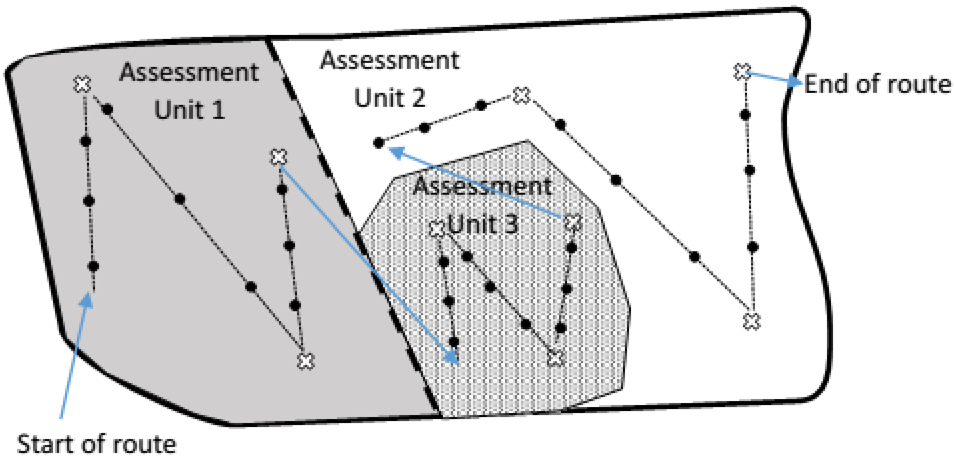

Figure 10. Field survey schematic as used in the Peatland Code condition assessment. After Taylor et al. (2015).

As mentioned under objective 1, it is also possible to add to the four Peatland Code categories the more heavily modified condition categories of Forest cover (split into broadleaf and conifer), Improved grassland, Cropland and Peat extraction (Table 1). Rewetted sites are unlikely to be candidates for development.

5.2.3 Depth of the Water Table

Water table measurement is not included in the Peatland Code. Any measure of dryness is purely visual on the day of inspection. However, mean annual water table depth is a useful indicator of peatland condition, will aid differentiation of the near-natural category from the modified category and indeed confirm the extent and effectiveness of drains in the drained category. It is important to recognise that it is the 'mean' value as any peatland will experience annual fluctuations with typically shallow water tables, or even inundation, in winter and deeper water tables during drier summer periods. In peatlands in good condition the water table should be within 5 cm of the surface, falling transiently to no more than 20–30 cm below the surface during drier periods (Stoneman and Brooks, 1997)[2]. This region of water table fluctuation defines the acrotelm, while the underlying permanently saturated zone defines the catotelm. Such diplotelmic peats are evidence of active peat formation. It should also be recognised that occasionally peatlands are found with a high water table but nevertheless with vegetation in poor condition due to non-hydrological pressures such as

[2] An updated version of this book is now available at: http://issuu.com/peat123/docs/conserving_bogs

over-grazing, pollution or burning. Peatlands in poor condition due to drainage, afforestation or peat extraction will have much lower mean annual water tables, perhaps 50 cm, extending to 90 cm or more during dry periods. However the actual water table depth in any particular situation will depend upon the depth of the drains, distance from the drains and the hydrological conductivity of the peat. Additionally, such peats will often have a collapsed acrotelm, or no acrotelm if it has been cut away, and are termed haplotemic. The catotelm is now at the surface, is no longer permanently saturated and subject to oxidation and erosion.

Water table depth is effectively monitored by the installation of dipwells. These are usually made from plastic piping inserted to a depth of 100 cm. Piping of 25 mm diameter is convenient though anything from 8–50 mm can be used (Stoneman and Brooks, 1997). There is a trade-off between narrower piping which is more responsive but more difficult to read and having a wider bore which is easier to read but slow to respond. 25 mm piping should be perforated down its length with up to 150 × 5 mm diameter holes (to allow ready exchange of peat water), with the bottom end closed off and the lower part protected with a nylon stocking (Gloudemans, 2015) though this latter precaution may not be always needed. It is useful to have an extra 25 cm of pipe protruding from the bog surface with a removable top cap in place. Ideally, the tops should be levelled to a fixed datum to enable absolute comparison of a series of dipwells (Wheeler and Shaw, 1995). Dipwells should be left for at least 24 hours after installation to allow for time to equilibrate; this is particularly the case where the water table is down to catatelmic peat which has a very much slower hydraulic conductivity in comparison to acrotelmic peat. They can easily be read by inserting a narrower plastic tube down the dipwell and blowing air down until bubbles are heard. Stoneman and Brooks (1997) describe a slightly more sophisticated device employing a stethoscope for microbore dipwells.

How many dipwells to install partly depends upon the size of the area under consideration. A minimum of five dipwells spaced apart within each Assessment Unit and covering the main flat areas, away from drains or other direct hydrological influences is recommended. However, a grid system across the site, or at least a straight transect across it, may be useful (Stoneman and Brooks, 1997). Measurements should be taken either weekly or fortnightly (Bonnett et al., 2009; van der Schaaf, 2002) for as long as possible. Ideally this should be for a full year but for practical purposes should be over at least six weeks during the winter months. Where short periods only are used, it may be possible to 'normalise' the data to a mean annual value if there are regular water table measurements being taken elsewhere within the same region, although the accuracy of this requires validation.

5.2.4 Peat Depth Assessment

Obtaining a reasonably accurate assessment of peat depth across a site will require a number of independent depthings. Unfortunately this number will vary from site to site as the variability in peat depth will depend on several factors such as variability in the underlying topology, position within the peatland complex, slope, impact of peat cuttings, etc. It has been estimated that to be 95% certain of obtaining a peat depth with a ±20% precision, then 38 samples are required and to increase the precision to ±10% then 145 samples are required (Smith et al., 2009). This is based on analysis of the Scottish Peat Survey data and may be biased towards larger peatlands formed in basin-type topologies. Blanket peat in more upland terrain may be expected to be more variable in thickness.

Scottish Government guidance for peat survey for developments suggests a 'low resolution survey' in which peat depths are taken at 100 m intervals[3]. The total number of depth measurements thus depends upon the size of the area under consideration. For a 1 ha site we would have ca. 100 depthings and for a 10 ha site ca. 1000 depthings. Thus even for a small site the numbers would soon approach those required for 10% precision. However, this assumes a fairly even depth across the site; where there are natural gradients in peat depth or very undulating underlying topology then the precision will be less. In contrast, the Peatland Code methodology would only result in a minimum of 12 measurements (or some low multiple of 12, depending upon the number of Assessment Units). It is suggested that, while this number may be adequate for checking whether the area is peat or not, it is insufficient for more precise depth measurements and that at least 100 depthings in total should be taken.

5.2.5 Peat Bulk Density Assessment

Routine measurement of peat bulk density has rarely been made. Within Scotland, the only examples are within the NSIS (National Soil Inventory of Scotland) and CS (Countryside Survey) projects and these are limited to 100 cm and 15 cm depths, respectively. The results from these surveys are described in detail in the response to objective 3. There are virtually no studies where spatial variation in bulk density has been measured over shorter (ca. 1 km) distances, the work by Frogbrook et al. (2009) being an exception. However, the indication is that bulk density will vary less than peat depth over such distances. Additionally bulk density may vary with depth but again the evidence (see objective 3 response) is that it will not vary greatly. Hence there is an argument for taking fewer bulk density measurements than depth measurements. A second consideration is more practical in that it takes much greater effort to take samples for bulk density. Smith et al. (2009), from a pragmatic angle, suggest a ratio of between 1:3 and 1:6 for bulk density sampling to depth sampling. On this basis, we would suggest ca. 16 points for bulk density measurement. In order to determine how bulk density varies with depth, there is a strong case for sampling the upper 0–15 or 0–30 cm horizon as

[3]http://www.gov.scot/Topics/Business-Industry/Energy/Energy-sources/19185/17852-1/CSavings/PSG2011

it is this surface region that may show increased bulk density. Below this the bulk density can be expected to be more uniform and so sampling every 50 cm is sufficient.

The equipment for bulk density sampling has some bearing on the sampling frequency. A box corer of the Cuttle and Malcolm (1979) type is convenient for sampling to 1.5 m. Below this only a Russian sampler (or similar) will suffice and this can be used to collect samples every 50 cm to the base of the peat. For shallow peats (50–100 cm) and alternative procedure is to dig a small pit and sample horizontally from the pit face. This method was used to obtain bulk density samples collected for the NSIS (Lilly et al., 2011).

5.2.6 Carbon Content Assessment

As for bulk density, there have been few studies of spatial variation in carbon content. While carbon content was routinely measured during the Scottish Peat Surveys, it was made on bulked samples from across individual bogs and so any information on spatial variation was lost. In mitigation, it is recognised that differences in carbon content due to depth or vegetation cover, while sometimes statistically significant, are materially small in peat soils (see objective 3 response). On this basis, it is sufficient and convenient to sample at the same frequency as for bulk density. Given the increased difficulty in analysing for carbon content, there is a good argument for using default values without too much loss in overall accuracy of resulting carbon stock values since uncertainties in peat depth and even bulk density are much greater. This option may require further consideration and possibly field validation.

5.2.7 Conclusions

The recommendation is that a peatland condition assessment that can be satisfactorily related to carbon stock and carbon emissions can be achieved by suitable modifications and extensions to the Peatland Code that is currently under development. The addition of woodland (conifer or broadleaf), improved grassland, arable land and peat cuttings, each of which are easily identified, can extend the current four Peatland Code categories to cover most situations on the ground. The current status of emissions data does not allow any further discrimination of condition classes. The measurement of water table depth will provide useful additional information on condition. Since the Peatland Code was set up for carbon stock assessment, the additional parameters of peat depth and bulk density should be measured at a suitable intensity. The measurement of carbon content may be regarded as optional and recourse to default values should be satisfactory.

5.3 Objective 3

5.3.1 Outline

Within this section we assess the relevant datasets for attributes that contribute to peat soil carbon stock (soil bulk density, carbon content, peat depth, peat area covered). These include the datasets that formed the basis of the ECOSSE II reports (Smith et al., 2009). Additional data has been acquired during the NSIS work though sampling in this was limited to the upper 100 cm of the soil or peat profile. Similarly, we report on data that was gathered during the Countryside Survey though this is further limited to the surface 15 cm (Reynolds et al., 2013). We assess the quality and age of these datasets. Additional datasets so far not included in any formal reports (additional peat depth measurements we have access to, e.g. the Scottish Wildlife Trust peat depth surveys of lowland raised bogs; various depth measurements from restoration projects, etc.) are also be considered in terms of the capacity to fill gaps in information. Finally, added value is given from ongoing analysis of data that have been recently digitised by James Hutton Institute staff, which formed part of the original Scottish Peat Surveys but have never been utilised. From this dataset, there is scope to estimate bulk density from moisture content and also relating these to vegetation and drainage records.

5.3.2 ECOSSE project

Smith et al. (2009), within the ECOSSE II project, summarised the data available at the James Hutton Institute on peat depth, bulk density and carbon content. Mean depths had been collated from 77 peat bogs, bulk density from 104 samples and carbon content from 240 samples. This dataset included 21 bulk density values from 10 sites sampled during phases 1 and 2 of the NSIS resampling. One of the major conclusions of the ECOSSE II project was that there was extremely limited peat dry bulk density data available for Scotland. There was insufficient data to determine, or even speculate on, any regional or spatial variation in bulk density and only limited indication as to how dry bulk density might vary with depth. The further limitations of these data are given the ECOSSE project report but in the context of this project it should be noted that part of this dataset on bulk density will have come from basin peat (raised bogs) as well as blanket peat. Additionally, the samples were not screened for those with low carbon content (<37%, see below). Tables 3 and 4 summarize the data for bulk density, carbon content and peat depth.

Compared to bulk density, rather more data was available on carbon content though again not enough to speculate on any spatial variation.

Coverage of peat depth was more extensive, being based primarily on data collected during the Scottish Peat Surveys (Department of Agriculture and Fisheries for Scotland, 1964; Department of Agriculture and Fisheries for Scotland, 1965a; Department of Agriculture and Fisheries for Scotland, 1965b; Department of Agriculture and Fisheries for Scotland, 1968) supplemented with more recent data; for details see Chapman et al. (2009). However, it was quite clear that large tracts of the country, particularly in the north and west, were very poorly represented. It should also be borne in mind that many of the areas previously surveyed were in raised bogs, as opposed to blanket peat, further reducing the data for actual blanket peat.

Table 3. Bulk density and % carbon values used by Chapman et al. (2009) in the estimation of carbon stocks. Values are means ± standard errors (number of values) applied at three depth intervals.

Depth (m)	0–0.3	0.3–1	> 1
	Bulk Density ($g\ cm^{-3}$)		
Basin peat	0.136 ± 0.022 (12)	0.114 ± 0.017 (17)	0.092 ± 0.004 (16)
Blanket peat	0.134 ± 0.009 (17)	0.123 ± 0.004 (34)	0.143 ± 0.010 (8)
	Carbon (%)		
Basin peat	51.1 ± 1.0 (25)	48.6 ± 1.1 (43)	60.8 ± 3.4 (2)
Blanket peat	50.6 ± 1.8 (21)	52.9 ± 0.7 (49)	54.6 ± 3.2 (7)
Eroded deep blanket peat*	50.1 ± 3.5 (10)	57.1 ± 0.4 (8)	54.2 ± 1.2 (2)
Eroded blanket peat	53.0 ± 0.9 (40)	55.2 ± 1.0 (33)	54.0 ± 3.2 (9)

*>1 m

Table 4. Peat map units and types on the 1:250 000 scale soil map of Scotland. Depths are means ± standard errors (number of values). After Chapman et al. (2009).

Unit	Peat Type	Weighted Average Depth (m)
3	Basin peat (>0.5 m)	2.87 ± 0.09 (360)
4	Undifferentiated blanket peat (>0.5 m)	1.34 ± 0.10 (652)
603*	Eroded basin peat (>0.5 m)	2.72 ± 0.39 (4)
604*	Deep blanket peat (>1 m)	2.30 ± 0.15 (166)
605*	Eroded deep blanket peat (>1 m)	1.70 ± 0.04 (30)
606*	Eroded undifferentiated blanket peat (>0.5 m)	1.32 ± 0.08 (116)
Peat contained within other map units	Blanket peat	1.12 ± 0.07 (48)
	Basin peat	2.87 ± 0.34 (8)
	Semi-confined peat†	1.28 ± 0.09 (71)

* codes allocated to subdivisions of 1:250 000 organic soil map units

† subdivision introduced for the Hydrology of Soil Types (HOST) classification (Boorman et al., 1995)

5.3.3 NSIS_2

The Hutton dataset has since been enlarged by the inclusion of values from phase 3 of the NSIS, which covered a much greater proportion of peatland areas. This gave an additional 128 bulk density and carbon content values from 42 sites for peat soils with a carbon content over 37%. An important note is that these were restricted to the upper 100 cm of any peat profile. What is summarised here (Table 5) is the data from 51 sites (147 values). Chapman et al. (2013) report on 52 peat soil sites but one site had horizons which all had %C< 37%. While the emphasis in this report is on blanket peats, data on basin peat has been included for completeness and comparison. In fact, of the 147 data values only 13 are from basin peat.

Table 5. Summary data for NSIS peatland sites

	Mean	SD	Min	Median	Max	SE of Mean
Bulk Density ($g\ cm^{-3}$)	0.122	0.0358	0.0574	0.118	0.260	0.00295
Carbon (%)	48.5	3.66	38.3	48.3	57.1	0.302

The NSIS sampling allows some limited inspection of any change with depth since samples were taken to approximately 80 cm and occasionally below 100 cm. Although sampling was by horizon, Table 6 shows the data apportioned to fixed depths to allow comparison with both the ECOSSE values (e.g. 0–30 cm) and the Countryside Survey values (0–15 cm, see below). Using ANOVA there was no significant effect of depth on bulk density but there was a significant increase in %C with depth

While there was no significant effect of depth on bulk density, it did increase significantly with degree of decomposition as indicated by the organic horizon type, i.e. whether fibrous, semi-fibrous or amorphous (Table 7). Generally organic horizons progress from fibrous through to amorphous with depth as the material becomes more humified. In parallel, there is a significant increase in %C (Table 7).

During the NSIS sampling the Von Post humification index (H) was recorded (von Post, 1922), where H values ranged from 2 to 10. There was a significant regression of bulk density on H ($P=0.001$) but the variation in bulk density explained was only 6.2%:

Dry bulk density ($g\ cm^{-3}$) = 0.0936 + 0.00425 × H   (r^2 = 6.2%; SEObs[4] = 0.0344)

[4] Standard error of observations

Table 6. NSIS bulk density and carbon content, partitioned by depth. Means followed by a different letter are significantly different ($P<0.05$).

Depth	n	Mean	Min	Max	SE of Mean
	Bulk Density ($g\ cm^{-3}$)				
0 – 15 cm	36	0.114 a	0.057	0.207	0.00531
15 – 30 cm	32	0.128 a	0.068	0.260	0.00684
0 – 30 cm	68	0.120 a	0.057	0.260	0.00433
30 – 100 cm	77	0.124 a	0.057	0.247	0.00414
100+ cm	2	0.100 a	0.098	0.103	0.00259
	Carbon (%)				
0 – 15 cm	36	46.2 c	38.3	48.8	0.354
15 – 30 cm	32	47.8 b	40.7	55.8	0.528
0 – 30 cm	68	47.0 bc	38.3	55.8	0.325
30 – 100 cm	77	49.7 a	38.8	57.1	0.450
100+ cm	2	51.7 ab	51.1	52.2	0.574

Including the horizon type, as in Table 7, did not improve the model and in fact the H index is really a finer scale of the three horizon types. While other studies have shown a much closer relationship between bulk density and humification index (e.g., Silc and Stanek, 1977), for Scottish peats it does not appear to be so useful. It could be argued that collecting samples for humification in order to estimate bulk density is not much simpler than determining dry bulk density directly.

Table 7. NSIS bulk density and carbon content, partitioned by horizon type where Of=fibrous, Os=semi-fibrous, Oa=amorphous. Means followed by a different letter are significantly different (P<0.05).

Horizon type	n	Mean	Min	Max	SE of Mean
	Bulk Density ($g\ cm^{-3}$)				
Of	12	0.101 b	0.068	0.141	0.00753
Os	54	0.117 ab	0.057	0.260	0.00524
Oa	81	0.129 a	0.072	0.247	0.00374
	Carbon (%)				
Of	12	45.7 b	38.3	47.5	0.751
Os	54	47.7 b	39.5	53.5	0.397
Oa	81	49.4 a	38.8	57.1	0.436

Within the NSIS peat soil category, not all were classified as bog in terms of vegetation, with some samples classed as either moorland, semi-natural grassland or woodland. Only those under semi-natural grassland had a significantly greater bulk density in comparison to the other vegetation types and there was no difference in %C (Table 8).

Table 8. NSIS bulk density and carbon content, partitioned by vegetation type. Means followed by a different letter are significantly different (P<0.05).

Vegetation type	n	Mean	Min	Max	SE of Mean
	Bulk Density ($g\ cm^{-3}$)				
Bog	100	0.118 b	0.057	0.247	0.0036
Moorland	25	0.131 b	0.073	0.161	0.0045
Semi-natural Grassland	7	0.169 a	0.126	0.260	0.0193
Woodland	15	0.111 b	0.057	0.154	0.0062
	Carbon (%)				
Bog	100	48.8 a	38.3	57.1	0.336
Moorland	25	48.6 a	43.1	56.2	0.759
Semi-natural Grassland	7	47.7 a	40.7	54.5	1.819
Woodland	15	46.8 a	39.5	53.6	1.190

Partitioning the data between major soil subgroups indicated a significantly greater bulk density in shallow blanket peat (i.e. 50–100 cm deep) when compared to either deep blanket peat or deep basin peat (i.e. > 100 cm deep); there were no significant differences in %C (Table 9). Ignoring peat type, shallow peat had a significantly higher bulk density than deep peat (P<0.001), 0.135 and 0.110 g cm^{-3}, respectively. Ignoring depth, blanket peat had a significantly higher bulk density than basin peat (P=0.011), 0.124 and 0.098 g cm^{-3}, respectively.

Table 9. NSIS bulk density and carbon content, partitioned by dominant major soil subgroup

Vegetation type	n	Mean	Min	Max	SE of Mean
	Bulk Density ($g\ cm^{-3}$)				
Deep basin peat	12	0.097 b	0.059	0.138	0.00714
Deep blanket peat	65	0.113 b	0.057	0.247	0.00394
Shallow basin peat	1	0.113 ab			
Shallow blanket peat	69	0.136 a	0.057	0.260	0.00438
	Carbon (%)				
Deep basin peat	12	49.5 a	42.7	53.4	0.856
Deep blanket peat	65	48.8 a	38.8	57.1	0.426
Shallow basin peat	1	43.2 a			
Shallow blanket peat	69	48.0 a	38.3	56.2	0.471

5.3.4 Countryside Survey

The Countryside Survey (CS) gives coverage of over 900 sampling points (from 5 plots within 195 1 km squares) across Scotland, although soil sampling was limited to the surface 15 cm (Emmett et al., 2010; Reynolds et al., 2013). Bulk density was determined from 5 cm diameter cores while the carbon content was determined in a subsample from the same core. While the data is, in theory, obtainable from the Countryside Survey website (http://www.countrysidesurvey.org.uk/data-access), only a part set was downloaded; the full set was kindly provided by the CS database manager Claire Wood, along with the vegetation data, data on the broad habitat, the ITE land classification code and the 'unofficial' NVC vegetation code associated with each point. It should be noted that the NVC code had been computer-generated from the plant species composition using the program MAVIS. Hence it can be inaccurate in some cases; the 'percent likelihood' of the NVC class was also provided which varied from 24-55% with a mean of 37%.

While the broad habitat is primarily vegetation-based, the bog habitat can be equated to some extent with peatland as the definition “covers wetlands that support vegetation that is usually peat-forming” and where heathland vegetation may be found on degraded sites where the depth of peat exceeds 50 cm it is still classified as bog. However, it is not clear whether the depth of the organic layer was determined during the survey. There were 234 sites classified as bog. However inspection of the bulk density values and revised carbon contents (see below) revealed about 20% of the soils having low %C (20–35%) associated with rather high bulk density values. The carbon content values in this dataset are actually determined by performing a loss-on-ignition (LOI) test on the soil and then converting the result to % C using a ‘universal’ conversion factor of 0.55. However, this factor is considered to be only approximate for peat soils, so an alternative conversion equation (based upon analysis of NSIS peat data) was also applied to calculate the peat carbon contents. The LOI values were back-calculated from the %C values supplied and then used to calculate revised %C (these are the values of %C used in all the following results).

$$\text{Revised \%C} = 20.204 \times e^{0.0093 \times LOI}$$

The carbon content across all soils is strongly bimodal, being either mineral or peaty (see, e.g., Emmett et al., 2010). Soils with intermediate contents are relatively rare and only occur where there has been cultivation, bioturbation or mixing by either wind or water. The more likely explanation for soil results from the CS dataset with intermediate %C values is that these soil samples were actually shallow organic layers (< 15 cm) that became mixed with the underlying mineral horizon during sampling. For the purpose of analysis of the CS data, it was decided to make a cut-off for samples with %C < 37%. This gave 189 ‘peatland’ sites. Of these 18 were from mosaic vegetation where the main alternative vegetation was Dwarf Shrub Heath. Hence it is likely that a fraction of these Bog sites were not actually peatland. By the same token it is likely that a number of woodland and grassland vegetation types were actually on peatland but it is difficult to diagnose which ones those might be. The data is summarised in Table 10. There was a weak but significant negative correlation between bulk density and carbon content (r=-0.370).

Data on the site locations are not disclosed by CS: “Survey squares locations are not disclosed to avoid any deliberate influences that could affect them or the features within them.” Access to the locations has been requested via Claire Wood but to date this has not been granted. It would be very useful to overlay the CS locations with soils data as this would give a much more solid basis for what may be peatland and, in more detail, possibly differentiate blanket peat, semi-confined peat and basin peat. Additionally, we may be able to overlay condition maps. What is available in very broad terms is the Environmental Zone description. This divides Scotland into ‘True uplands’, ‘Intermediate uplands and Islands’ and ‘Lowlands’.

Table 10.Summary data for CS peatland sites

	Mean	SD	Min	Median	Max	SE of Mean
Bulk Density (g cm^{-3})	0.105	0.052	0.028	0.092	0.340	0.0038
Carbon (%)	47.3	3.1	37.1	48.5	50.5	0.22

Table 11. CS Peatland data, subdivided by Environmental Zone

	Lowlands	Intermediate uplands and Islands	True Uplands
n	12	102	75
Bulk Density (g cm^{-3})	0.086	0.110	0.101
Carbon (%)	47.2	47.3	47.2

Based on ANOVA, there was no significant difference between these zones (Table 11). Some of these sample points will be from basin rather than blanket peat and it is tempting to suggest that these will be most likely to occur in the 'Lowlands' zone. However, the proportion of 'Priority Habitat' blanket peat (see below) in the Lowlands (75%) is similar to that in the Uplands (77%), with a much lower proportion (36%) in the Intermediate zone.

There is an additional marker in the dataset for 'Priority Habitat' Blanket peat, though there must be blanket peat within the non-priority areas and it is not clear how the priority status was determined for any particular site. "Priority Habitats are those which have been identified in the UK Biodiversity Action Plan as being at risk: such as those with a high rate of decline; those that are functionally critical; and those which are important for Priority Species" (Norton et al., 2009). If for blanket peat it is the last criteria then priority blanket bog may relate to those areas in better condition.

Table 12. CS Peatland data, subdivided by priority habitat

	'Priority' Blanket Bog	Non-priority
n	104	85
Bulk Density ($g\ cm^{-3}$)	0.100	0.111
Carbon (%)	47.7	46.8

Based on ANOVA, the 'Priority' Blanket Bog (and possibly sites in better condition) had a slightly higher carbon content than the Non-priority sites (significant at P=0.04) and a 10% lower bulk density though this was not statistically significant (P=0.14) (Table 12).

Vegetation compositions, NVC classes and ITE Land Classification data were all obtained, which may allow further break-down of the primary bulk density and carbon content data to give some differentiation and the possibility of linking the values to condition. Time did not permit examination of the vegetation data but these are summarised within the generated NVC classes. Bulk density and %C for each NVC class are presented in Table 13. For quite a number of categories the numbers are too small to make any conclusions. ANOVA was performed where n≥6 but the value of F for the bulk density values was not significant (P=0.119). The ANOVA for the %C values was significant (P=0.012) with M19a and M16a having significantly higher %C values than U16c and M15. Looking at the four most common groups (n≥21) by ANOVA showed significant differences with M16a having a rather lower bulk density than M15 or M16 with M15c being intermediate. The more frequent occurrence of Sphagnum within M16a in comparison to the others may account for the lower bulk density. The same four groups also showed significant differences in %C with M15 being significantly lower than the others.

In an effort to aggregate some of the smaller classes, the NVC classes were put into a seven vegetation classes (Table 14). H9, H12, M15 and M16 may be regarded as degraded blanket bog (DBB) where the peat extends beyond 50cm (Joint Nature Conservation Committee, 2006) while M19, M20 and M25 are part of the main blanket bog (MB) classes and M1-M3 are bog pool (BP) communities. Other communities were those characteristic of heath (H), Fen Marsh and Swamp (FMS), acid grassland (U) and woodland (W). However ANOVA showed no real differences either for bulk density or for %C. It is perhaps worth noting that communities that might be considered to be in poorer condition (DBB + H + U + W) accounted for 91% of the sample points, broadly agreeing with the statement that only 18% of blanket bog in the British Isles is in natural or near-natural condition (Littlewood et al., 2010). Compared to the better communities (BP + MB + FMS) there was a trend for these poorer sites to have a higher bulk density (0.107 cf. 0.086) and lower %C (47.2 cf. 48.4) but these were not statistically significant (P=0.12 and 0.11, respectively).

The division into ITE Land Classes revealed some, perhaps surprising, differences; the ANOVA was highly significant ($P<0.001$). Figure 11 summarises the bulk density data and the land classes are given in Table 15. The results actually suggest a gradient in bulk density, being higher in the north and decreasing to the south-west. The carbon content follows a similar pattern (Figure 12) though in reverse and less pronounced. The ANOVA on the differences was also significant (P=0.001).

Table 13. CS Peatland data, subdivided by NVC unit. Where letters are given, values followed by the same letter are not significantly different (P<0.05).

NVC Unit	Vegetation name	Veg. Class*	No. samples	Dry Bulk Density	%C
H1	Calluna vulgaris – Festuca ovina	H	1	0.081	49.3
H10a	Calluna vulgaris – Erica cinerea (subcommunity)	H	2	0.114	47.1
H12a	Calluna vulgaris – Vaccinium myrtillus (Calluna subcommunity)	DBB	6	0.091	48.5
H2c	Calluna vulgaris – Ulex minor (Molinia caerulea subcommunity)	H	3	0.068	43.2
H4	Ulex gallii – Agrostis curtii	H	2	0.117	49.1
H9a	Calluna vulgaris – Deschampsia flexuosa (Hypnum cupressiforme subcommunity)	DBB	1	0.060	49.2
H9e	Calluna vulgaris – Deschampsia flexuosa (Molinia caerulea subcommunity)	DBB	1	0.059	48.8
M1	Sphagnum auriculatum pool	BP	1	0.041	48.7
M15	Scirpus cespitosus – Erica tetralix	DBB	31	0.121a	45.9b
M15c	Scirpus cespitosus – Erica tetralix (Cladonia subcommunity)	DBB	54	0.102ab	47.5a
M16	Erica tetralix – Sphagnum compactum	DBB	21	0.121a	47.1ab
M16a	Erica tetralix – Sphagnum compactum (typical subcommunity)	DBB	26	0.087b	48.6a
M19a	Calluna vulgaris – Eriophorum vaginatum (Erica tetralix subcommunity)	MB	6	0.076	49.2
M2	Sphagnum cuspidatum pool	BP	2	0.081	49.2
M20	Eriophorum vaginatum	MB	1	0.117	49.8
M25	Molinia caerulea – Potentilla erecta	MB	1	0.150	39.4
M3	Eriophorum angustifolium pool	BP	4	0.110	49.0

M4	Carex rostrata – Sphagnum recurvum	FMS	1	0.058	46.6
M6	Carex echinata – Sphagnum recurvum/auriculatum	FMS	1	0.042	49.0
U16c	Luzula sylvatica – Vaccinium myrtillus (species-poor subcommunity)	U	9	0.121	46.1
U2	Deschampsia flexuosa	U	1	0.149	49.2
U2b	Deschampsia flexuosa (Vaccinium myrtillus subcommunity)	U	3	0.130	46.3
U5a	Nadus stricta – Gallium saxatile (species-poor subcommunity)	U	2	0.193	45.5
U5d	Nadus stricta – Gallium saxatile (Calluna vulgaris – Danthonia decumbens subcommunity	U	1	0.126	47.3
W4	Betula pubescens – Molinia caerulea	W	8	0.098	46.1

*H-Heath; DBB-Degraded blanket bog; BP-Bog pool; MB-Main bog; FMS-Fen,Marsh, Swamp; U-Acid grassland; W-Woodland

Table 14. CS Peatland data, subdivided by Vegetation class (see Table 12 for classes)

Veg. class	No. samples	Mean	Minimum	Maximum	S.E.mean
BP	7	0.092	0.032	0.256	0.029
DBB	140	0.105	0.028	0.341	0.004
FMS	2	0.050	0.042	0.058	0.008
H	8	0.093	0.047	0.150	0.012
MB	8	0.090	0.048	0.150	0.013
U	16	0.133	0.041	0.265	0.014
W	8	0.098	0.031	0.203	0.020

Table 15. ITE Land Classification of Great Britain (2007)

No.	No. samples	Description
25	0	Hard/mixed coasts, S-W Scotland
26	7	Coastal plains/soft coasts, S-W Scotland
27	8	Isolated hills/mountain summits, W Scotland
28	4	Upland valleys/low mountains, S Scotland
29	36	Low mountain slopes/upper river valleys, Highlands
30	8	Round mountains/broad upper ridges, S Scotland/Highlands
31	12	High mountain summits/ridges/valleys, Highlands
32	19	Steep valley sides/intermediate mountain tops, W Highlands
33	2	Undulating plains/gently sloping valleys, E Scotland
34	0	Flat plains/gently sloping lowlands, central & S Scotland
35	3	Low hills/undulating lowlands, Scotland except W
36	6	Shallow valleys/low hill plateaux, throughout Scotland
37	16	Inner rocky/mixed coasts/complex topography, W Scotland
38	33	Outer rocky/mixed coats/low hills, W Scotland/Islands
39	11	Rocky/mixed coasts/low hills, N Scotland/Islands
40	24	Shallow hills/complex coastlines, N Scotland/Islands

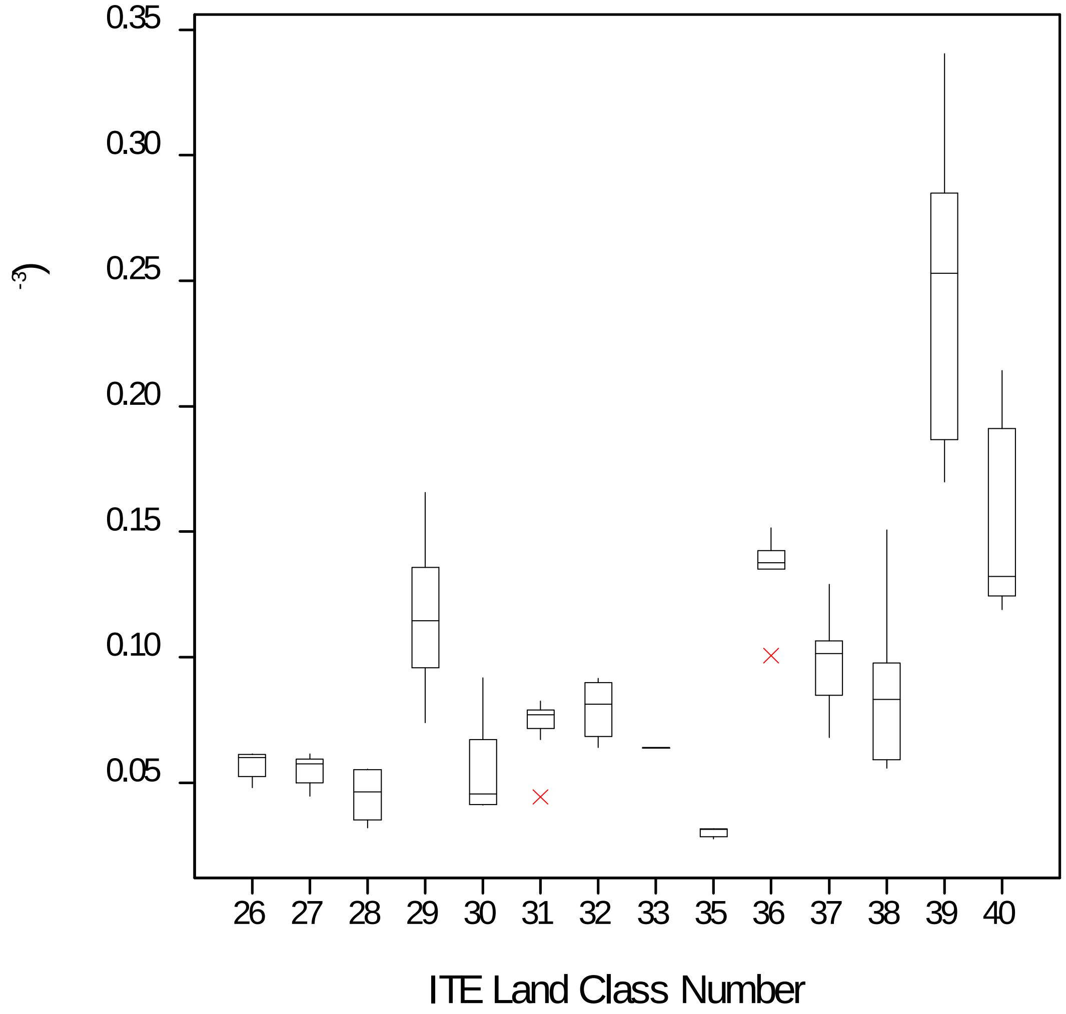

Figure 11. Variation in bulk density with ITE Land Classification (see Table 15 for an explanation of the class numbers).

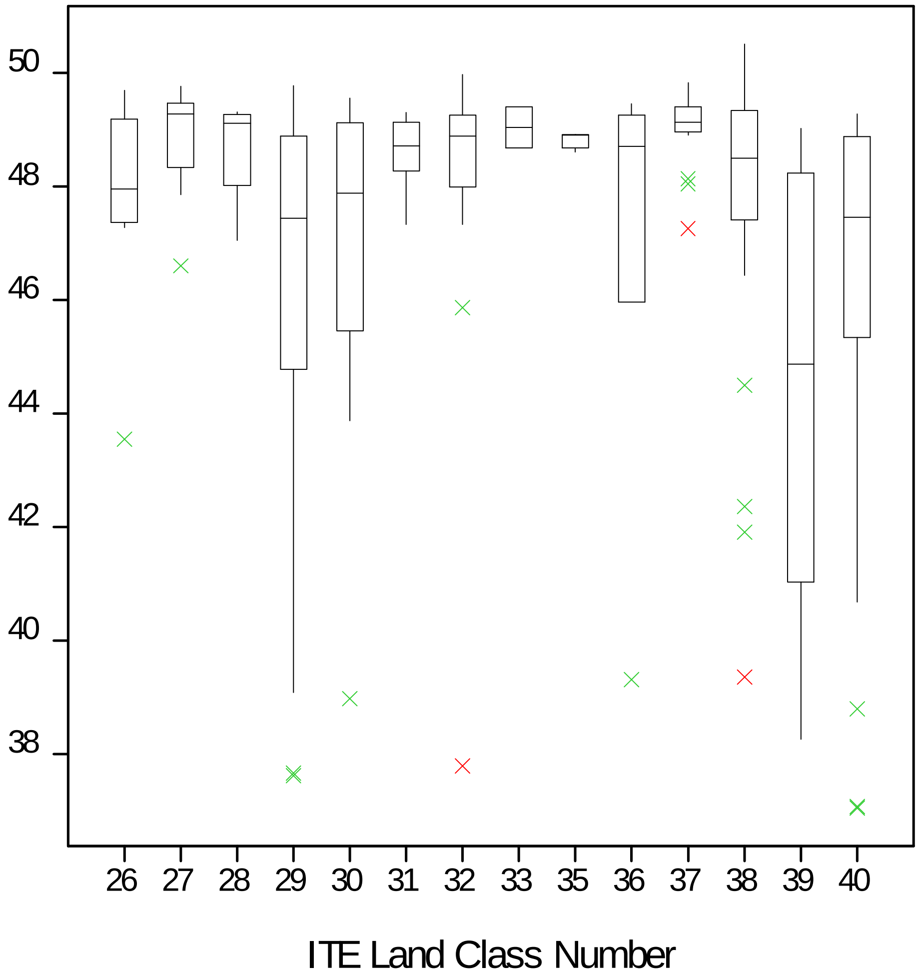

Figure 12. Variation in carbon content with ITE Land Classification (see Table 15 for an explanation of the class numbers).

5.3.5 Peat Surveys

Data which formed part of the Scottish Peat Surveys and was only found as figures within original reports has now been digitised and analysed. Bulk density was not directly measured as part of the original surveys. However, from this dataset, there was scope to estimate bulk density using a pedotransfer function based upon the moisture and ash contents (Chapman et al., 2015). Figure 13 shows bulk density over depth for both blanket and basin peats. The apparent increase at the very surface is an artefact of the pedotransfer function which over-estimates bulk density where the soil is not saturated. Hence, essentially there is little evidence of much change with depth until about 5 m where there is some decrease in bulk density (for those peats that are that deep). It is also clear that blanket peats have a slightly higher bulk density than basin peats. Replotting the data against the maximum depth of each particular peat bog (Figure 14) reveals that the deeper the particular bog, the lower the mean bulk density. Also, there is not a lot of difference in this plot between blanket bogs and basin bogs suggesting that the reason basin peats have a lower bulk density than blanket peats is not so much an intrinsic difference in the peat per se but that basin peats tend to be deeper than blanket peats.

Humification index was also recorded during the Peat Surveys. However, regression of the estimated bulk densities against H, while significant ($P=0.004$), only explained less than 1% of the variation.

In addition, the four volumes covering the Peat Surveys (see above) were examined for information on drainage condition and vegetation. Drainage was not recorded quantitatively during the surveys but described as part of the surface features. We made a semi-quantitative index, scored as follows: '-' (No mention of drainage or only natural drainage); '+' (Little drainage or only sheep drains (shallow 20 inches deep), now overgrown (inoperative, unsatisfactory, not maintained); '++' (Has been drained in past with more frequent/deeper drains (one metre or more), but now not working); '+++' (Drained and still effective (this would be case for cut-over areas or areas recently prepared for harvesting or forestry)). Vegetation was recorded as a list of species present within the area; in some cases this was semi-quantified by descriptors such as 'frequent', 'abundant' and 'dominant'. Hence the vegetation was scored on a scale of 1–3 (present–dominant) accordingly. However, there remains some caution in the resulting drainage and vegetation scores as they rely on interpretation of the descriptive text and assume some consistency across all the surveys. Unfortunately, there was no relationship between these two condition indicators and bulk density (restricting this to the surface, 0–50 cm, bulk density values). The '++' drainage category had the greatest bulk density (there were only two values in the '+++' category) but this was not statistically significant. Multivariate analysis of the vegetation patterns showed no relation with bulk density.

Multiple linear regression analysis was used in order to find a combination of parameters that might be used to estimate bulk density. Bulk density could be explained by a linear combination of maximum depth (as in Figure 14), ash content and the Y-coordinate, where the Y-coordinate is the northing of the bog map coordinate. All were significant at $P<0.001$; however, in practice the addition of ash content and Y-coordinate gave very little benefit to the prediction and most of the total variation explained was explained by the maximum depth. Omitting the bulk density values for depths < 50 cm (since these are likely to be over-estimated, see above), the overall regression on maximum depth (Mdepth) was:

Dry bulk density (g cm^{-3}) = 0.114 – 0.00500 × Mdepth (m) (r^2 = 22.9%; SEObs = 0.0143)

For raised bogs only:

Dry bulk density (g cm^{-3}) = 0.110 – 0.00470 × Mdepth (m) (r^2 = 17.3%; SEObs = 0.0150)

For blanket bogs only:

Dry bulk density (g cm^{-3}) = 0.107 – 0.00312 × Mdepth (m) (r^2 = 7.1%; SEObs = 0.0126)

Where data on maximum peat depth is available, these equations would give slightly improved estimates of bulk density in comparison to just using overall mean (default) values.

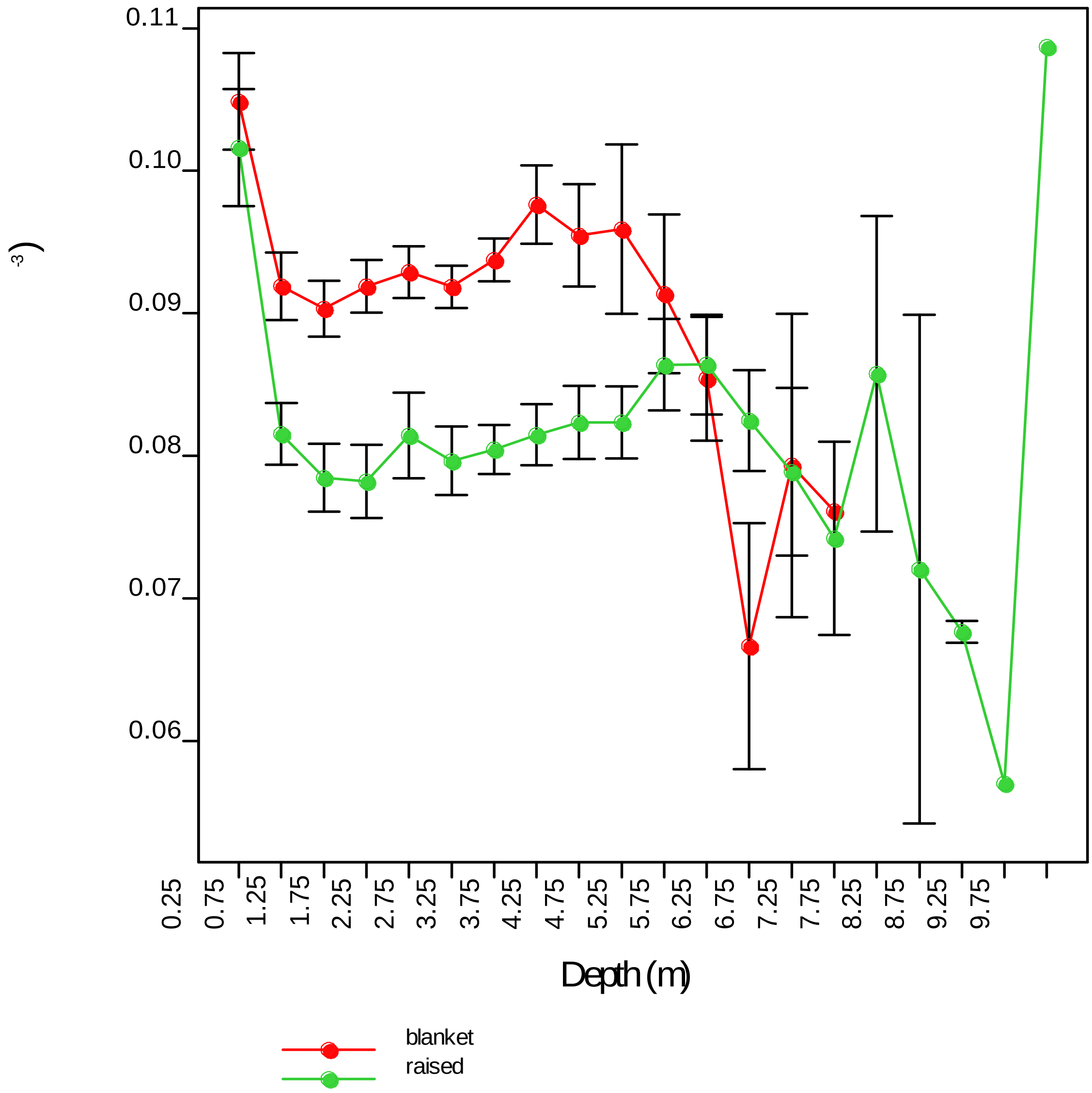

Figure 13. Bulk density over depth as determined using a pedotransfer function and using data from the Scottish Peat Surveys

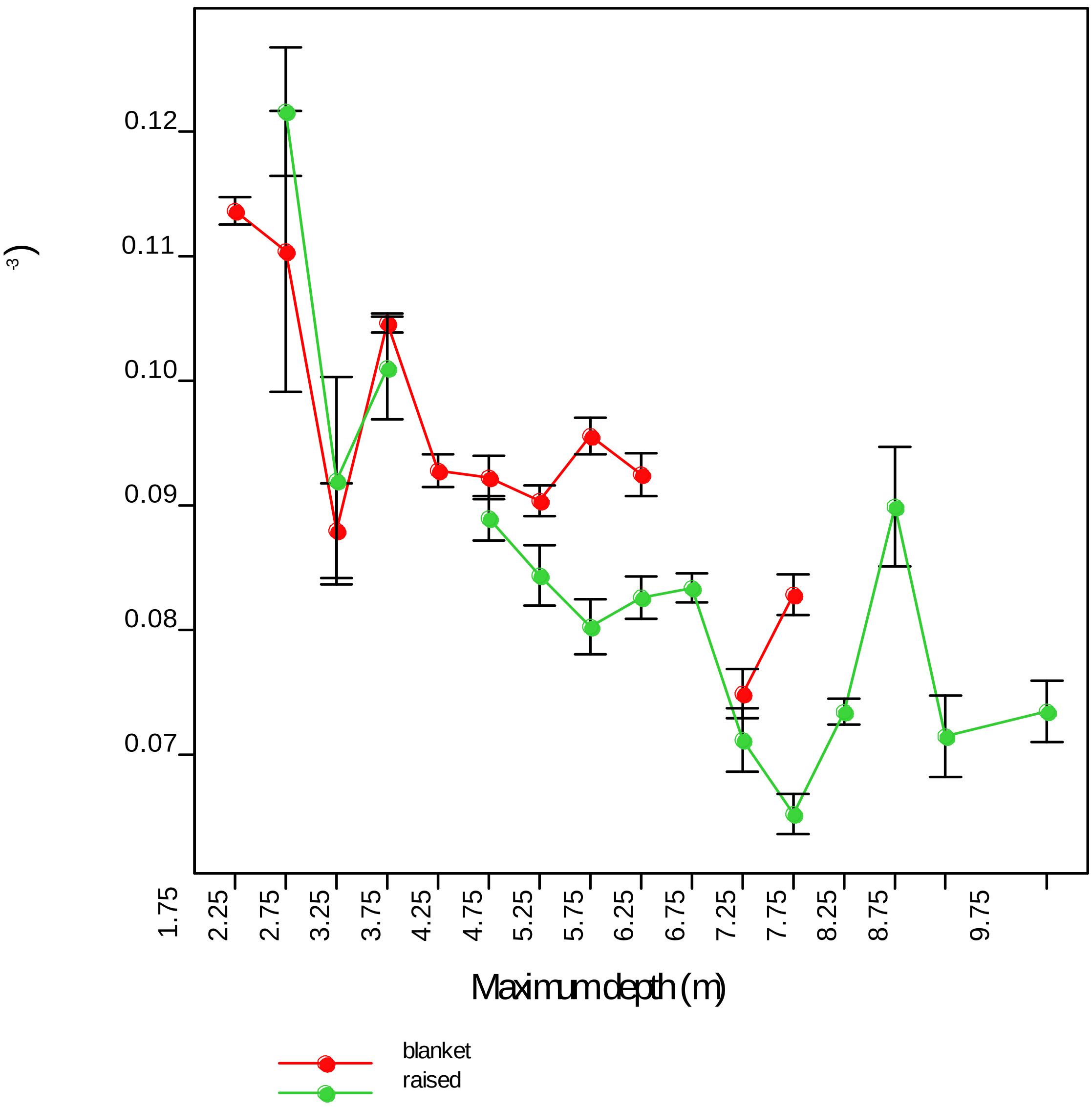

Figure 14. Bulk density as determined using a pedotransfer function plotted against the maximum depth of the bog from which the data was obtained

5.3.6 Other data sources

A number of other sources of data on bulk density, carbon content and peat depth have been explored:

The possibility of obtaining windfarm peat data was explored with the Forestry Commission. Initially Emma Stewart (Forestry Commission Scotland, Scottish Lowlands Forest District) was hopeful of this but subsequently heard that 'The windfarm folk are not going to release the data'. We have not been able to push this door further either via SNH or SEPA. It is possible that individual windfarm companies might be prepared to divulge data but it might be on condition that locations are not disclosed. The most promising avenue is if the public release of data is made a condition for planning consent being given. We await further input from SEPA/SNH as to whether they can obtain windfarm data from contractors.

1. Russell Anderson (Forestry Commission; FC) was also queried for any recent FC data on bulk density. MLURI did access a set of bulk density data from FC prior to the ECOSSE II project. However, there was no further data gathered apart from some detailed peat depths taken at Bad a Cheo (blanket bog) and at Flanders Moss (raised bog).

2. We are aware of a more recent dataset covering peat depths though this is restricted to lowland bogs only (Matthews et al., 2012) and has not been followed up.

3. Peat depth data is currently being gathered under the Peatland Action Plan. In order to receive funding, there is a requirement that contractors perform a complete peat survey of the site at, at least, 100 m intervals. Our understanding is that this data will be publically available from SNH. Currently there are 105 restoration sites although not all these will be blanket peat. We have contacted Estelle Gill to determine who is collating this information and in fact offered to assist in the process. The answer at the moment is that this will take some time to sort out.

5.3.7 Conclusions

- It is clear that blanket peats tend to have higher bulk density values than basin peats. This was borne out by both the NSIS data and that computed from the Peat Surveys. Unfortunately we were unable to gauge this from the CS data as this information was not specifically included. If at some point we can access the CS locations then this calculation would be possible.
- There is evidence that bulk density does not vary greatly with depth though deeper bogs tend to have overall smaller bulk density values. This will, to a very limited extent, mitigate against deeper bogs having a greater carbon stock. Some estimation of bulk density can be made, taking into account the depth of the bog.
- There is limited evidence on how peatland condition impacts bulk density. From the CS results (though for surface samples only), 'priority' blanket bog, which we

presume to be in better condition, had a lower bulk density than non-'priority' bog. Vegetation classes (NVC classes) which indicated better condition (non-degraded) also showed lower bulk density values. It was clear from both the NSIS and CS data that replacement of bog vegetation with more grassland vegetation was accompanied by a marked increase in bulk density. From the Scottish Peat Surveys there was a trend for more intense drainage to be reflected in higher surface bulk density values.

- Carbon content values were much less variable than bulk density values. Values increased slightly with peat depth and degree of decomposition but did not differ between blanket and basin peats.
- For changes and values of bulk density below 1 m we are still forced to rely on data obtained by pedo-transfer function as actual measured values are very scarce.

6 Overall conclusions and recommendations

6.1 Overall conclusions

The primary question within this study was whether peatland carbon stock could be related to peatland condition. Having examined the available evidence, the overall conclusion is that currently it cannot be quantified unequivocally, although there are indications that carbon stock parameters (dry bulk density, carbon content and, possibly, peat depth) do vary with condition. One of the problems is in defining what is meant by condition and since this is inevitably a continuum, one is restricted to looking at broad categories. Carbon stocks (or the underlying parameters) within such broad categories have never been systematically measured. The paucity of data revealed by the ECOSSE report has been enlarged by more recent surveys but the objectives of these was to gather representative national data rather than focus on condition categories.

We are slight better placed in relating carbon emission factors to different condition classes though the values given carry large uncertainties. Also we have very poor information on the condition of peatlands across Scotland. In the first place, there are problems of mapping the fine scale location of peatlands across the country. Secondly, determining condition across wide areas is challenging though various remote sensing techniques are showing promise. It has been demonstrated that drains can be mapped, though knowing the effectiveness of observed drains remains to be determined. There are advances in picking out burnt areas – obtaining precise timing is difficult but new products may improve the situation. Multi-spectral data can now give clues as to vegetation cover. However, in all these there is the need for on the ground assessment, including determination of the effects of drainage.

There are advantages in adopting the ‘Peatland Code’ protocol where on the ground assessments of broad peatland condition can be linked to emission factors. It is perhaps worth noting that the intention of estimating these emission factors is not to replace the carbon losses calculated in the carbon calculator but rather to give comparative figures if the site is either left as is or is restored to some degree. Extension of the protocol to include measurements of total peat depth, bulk density and, optionally, carbon content would enable estimation of total carbon stocks. Carbon content is judged to be optional from the point of view that default values, which do not show a great deal of variation, could be used. The ‘Peatland Code’ provides for a fairly simple protocol that non-specialists should be able to execute, though some skill might be required in recognising evidence of factors like burning, grazing, etc. It is considered that water table measurement would be a useful addition to condition assessment with the drawback that this would take some time to monitor satisfactorily.

The original ECOSSE dataset of bulk density and carbon content values (n=104 for bulk density) has been extended by the NSIS dataset (n=147; 21 values were common to both). The value of the NISIS is that it is a representative national survey rather than a collection of scattered values. The CS survey (n=189) is also a national representative sample but has the disadvantage that samples were restricted to the surface 15 cm. The Peat Survey dataset (n=919) has the advantage that values extend below the 100 cm of the NSIS survey to the base of the bog but has the disadvantages of being derived values and being restricted to the major (and deeper) peat reserves. In terms of providing unbiased values of bulk density (0.122 g cm^{-3}) and carbon content (48.5%) the NSIS dataset is to be preferred. Where values dependent upon depth, degree of decomposition, vegetation or major soil subgroup are required, the values in tables 6-9 may be used. The values of bulk density and carbon content provided in the CS dataset and those of estimated bulk density in the Peat Survey dataset tend to be slightly lower than the NSIS values but not significantly so.

6.2 Recommendations

1. While it is beyond the remit of the present study, there is clearly a need to refine the emission factors within each of the different condition categories. This will be accomplished by initiating further targeted studies and by incorporating other relevant datasets as they become available. This will be done by those involved in further tuning the UK figures for IPCC reporting but a watching brief on this would be helpful.
2. Similarly, within the area of remote sensing developments aimed at assessing peatland condition there are a number of developments that may see fruition over the next few years, as well as more developed techniques like satellite imagery, aerial photography and Lidar becoming cheaper and more accessible. Again developments should be closely followed.

3. More specifically, there is a need for mapping drainage across the country; the methodology is available but it does require some investment in time. Associated with this is the need to better understand the impacts of drainage. Over what distance drain exert an influence is poorly understood and how this might be influenced by drain depth, slope, peat type, etc. is still unclear. Since this feeds directly into the carbon calculator, such studies would be very informative.
4. The protocol derived from the Peatland Code needs to be assessed by relevant stakeholders, firstly by review and, secondly, by field testing. It would be pertinent to follow any developments of the Peatland Code itself, which is still very much in its infancy and may well see future improvements as it becomes more used.
5. Carbon stock parameters (peat depth, dry bulk density, carbon content) should be measured over the whole peat profile at sites under defined condition classes, i.e. near-natural, modified, drained, eroded, to test how they might vary. Only when this has been done in sufficient detail can we answer the question of how peatland condition might impact carbon stock estimates.
6. The observations from the Peat Survey, i.e. minimal change of bulk density with depth, dependence of bulk density on total peat depth, slight differences between raised and blanket peats, need to be confirmed by direct measurements of bulk density, particularly collecting data from below 100 cm.
7. The current national dataset on peat depth contains bias towards deeper peat. Data should be collected from areas of shallower peat deposits, particularly covering examples from the central and north-west highlands of the country.
8. Renewed effort should be made to obtain peat carbon stock data from windfarm developments, as well as data from ongoing restoration projects under the Peatland Action Plan. In the same vein, access to CS locations would enable much firmer conclusions to be made from the CS data.

7 Acknowledgements

The authors thank Malcolm Coull and David Donnelly for help with the soils database and mapping. We thank Claire Wood (CEH Lancaster) for assistance with downloading the CS data. We also thank Mary-Anne Smyth and Emily Taylor (Crichton Carbon Centre) for helpful discussions and early sight of the Peatland Code field protocol.

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Appendix.

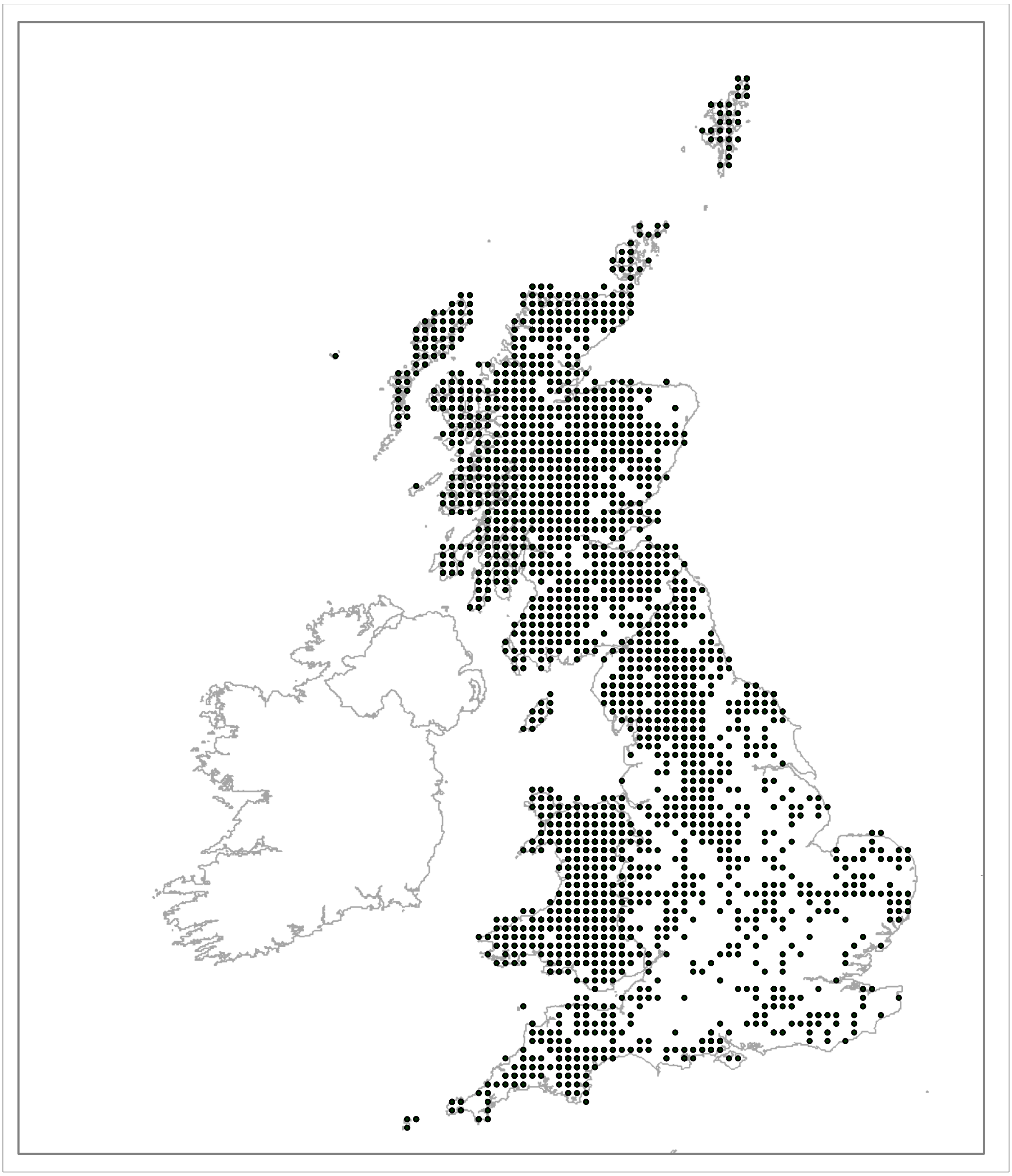

Figure A1. Coverage of the upland plant community types across the UK (Averis et al., 2004).

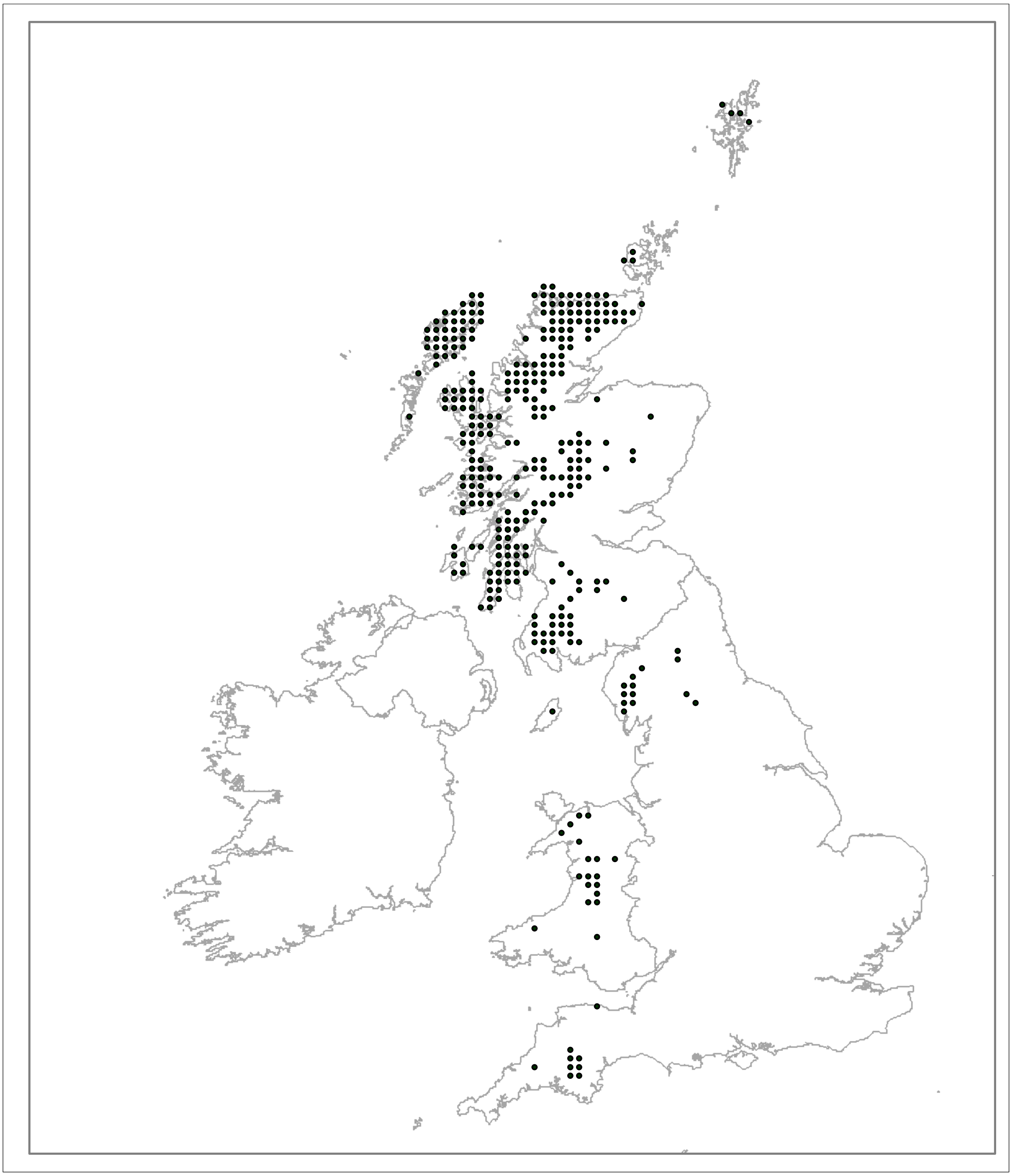

Figure A2. Distribution of the M17 Scirpus cespitosus-Eriophorum vaginatum blanket mire communities. As per Rodwell et al. (1991), this should be one of the less impacted blanket mire community types, however, the more Cladonia-rich sub communities within M17 can be indicative of climatic changes towards drier habitat, but also burning, peat cutting and drainage. The available datasets cannot be subdivided to give indications of such sub communities at present.