Palaeoecological studies as a source of peat depth data: A discussion and data compilation for Scotland

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SUMMARY

The regional/national carbon (C) stock of peatlands is often poorly characterised, even for comparatively well-studied areas. A key obstacle to better estimates of landscape C stock is the scarcity of data on peat depth, leading to simplistic assumptions. New measurements of peat depth become unrealistically resource-intensive when considering large areas. Therefore, it is imperative to maximise the use of pre-existing datasets. Here we propose that one potentially valuable and currently unexploited source of peat depth data is palaeoecological studies. We discuss the value of these data and present an initial compilation for Scotland (United Kingdom) which consists of records from 437 sites and yields an average depth of 282 cm per site. This figure is likely to be an over-estimate of true average peat depth and is greater than figures used in current estimates of peatland C stock. Depth data from palaeoecological studies have the advantages of wide distribution, high quality, and often the inclusion of valuable supporting information; but also the disadvantage of spatial bias due to the differing motivations of the original researchers. When combined with other data sources, each with its own advantages and limitations, we believe that palaeoecological datasets can make an important contribution to better-constrained estimates of peat depth which, in turn, will lead to better estimates of peatland landscape carbon stock.

KEY WORDS: blanket bog, carbon stock, dataset, historical, management, soil, United Kingdom

THE NEED FOR PEAT DEPTH DATA

With increasing recognition of the globally significant quantities of carbon stored as peat, peatland science, management and conservation are increasingly motivated by a ‘carbon agenda’ (Bain *et al.* 2011). However, uncertainties in assessments of the peatland carbon stock are large and progress towards better estimates is relatively slow, primarily due to the limited availability of underlying data. In a global context the peatlands of the United Kingdom (UK) are very well-studied, but even here estimates of peatland carbon stock vary considerably, from 3000 to more than 7000 MtC (Lindsay *et al.* 2010), and are complicated by varying data sources, methodologies and definitions.

Yu (2012) outlines three approaches which have been used to estimate peatland carbon stocks, based on (i) the timing of peatland initiation and carbon accumulation rates; (ii) carbon density *per* unit area, and (iii) peat volume. The latter approach has been by far the most widely implemented and requires data for peatland area, peat depth, bulk density and carbon content. Of these four attributes, peatland area is best constrained and carbon content is comparatively invariable. There is, however, greater uncertainty with regard to bulk density and peat depth. Lindsay *et al.* (2010) argue that both these factors are equally important in improving peatland carbon estimates. Therefore, changes in estimates of peat depth will strongly influence estimates of carbon stock (Chapman *et al.* 2009). Previous studies producing estimates of peatland carbon have often made assumptions about peat depth based on very limited empirical evidence (Cannell *et al.* 1993, Robertson 1971) and recent studies of soil carbon have often been restricted to the top metre, excluding much of the peatland carbon stock (Bradley *et al.* 2005). Peat depth is a complex property which is strongly influenced by underlying topography, which means it can vary greatly over relatively short distances. This is particularly true of the upland blanket mires which dominate UK peatlands.

A large and previously unexploited resource of peat depth measurements can be found within the palaeoecological literature. This has the potential to complement other datasets and improve current estimates of peat depth. It may also be desirable to improve estimates of bulk density but, because there are few published measurements, a compilation is likely to have less impact on carbon stock estimates than a catalogue of published peat depths. For these reasons, we consider peat depth to be the factor with greatest potential for improving peatland carbon stocks using existing data sources.

EXISTING PEAT DEPTH DATASETS

Measurements of peat depth are collected and collated for many reasons. Depth data are often required as part of the planning process for development in areas with peatland. For instance, the Scottish Government's 'carbon calculator' tool for wind farm development requires data on peat depth (Nayak *et al.* 2010), and peat depth is a criterion in applications to plant trees on peat (Patterson & Anderson 2000). Much information was collected historically during attempts to identify extractable peat resources and develop peatland silviculture, for instance the Scottish Peat Surveys (Department of Agriculture and Fisheries for Scotland 1964, Chapman *et al.* 2009) and various Forestry Commission datasets (Cannell *et al.* 1993). Depth data are now widely collected in conjunction with attempts to conserve and restore peatlands, and are required from recipients of funding for peatland restoration under schemes such as Scottish Natural Heritage's Peatland Action programme (McBride 2014). Large collections of depth data are maintained by conservation organisations such as the Yorkshire Peat Partnership, Moors for the Future and the National Trust for Scotland, although much of the information is not compiled or easily accessible.

The variety of purposes for which these datasets were produced means that none of them is likely to be truly representative of the national resource. Datasets compiled as part of proposals to develop peatlands for wind farms and forestry will probably be biased towards shallower, more accessible peat (Lindsay *et al.* 2010), whilst those compiled to support historical aspirations to exploit peat for fuel and horticulture may be biased towards larger and more accessible sites. Data compiled within peatland restoration projects will tend to represent peatlands which require restoration, excluding more natural sites. There is clearly a place for alternative datasets which can contribute to the whole picture by providing both additional data, and data which are less (or at least differently) biased. Here we propose that data from palaeoecological studies can be a valuable resource of additional data which has some distinct advantages, as well as some disadvantages.

THE POTENTIAL VALUE OF PALAEOECOLOGICAL STUDIES

For more than a century palaeoecologists have been sampling peatlands to address a wide variety of questions relating to mire development, vegetation history, archaeology, climate change, pollution and many other topics. While peat depth was nearly always peripheral to the focus of these studies, it was nevertheless frequently determined and recorded. We believe that this source of depth data has both advantages and disadvantages. On the positive side:

a) Palaeoecological studies have been conducted widely and the potential depth data resource is considerable for many countries. While the questions that have motivated palaeoecologists have varied greatly, the lack of previous study in a region has often been seen as justification for future study. This means that palaeoecological studies tend to provide good landscape-scale coverage.

b) Depth measurements from palaeoecological studies are likely to be more accurate than many alternatives. The majority of currently available peat depth measurements have been made by simple manual depth probing, which involves inserting a metal rod into the peat until a point of resistance is met; then depth is measured and location recorded. This approach can lead to inaccurate data because the probe may make contact with mineral clasts, inwash layers or wood remains causing total depth to be underestimated, or may penetrate into soft clay and gyttja layers beneath the peat so that depth is overestimated (Parry *et al.* 2014). Good probing practice may help minimise this error. For example, the use of an auger tip can provide a means to drill through impeding layers and can also provide evidence that the mineral substrate has been reached (Department of Agriculture and Fisheries for Scotland 1964). Thus, the quality of the probing data will depend very much on the methods used and the practice employed by the surveyor. While there is little information on the comparative accuracy of various probing techniques, a comparison with ground penetrating radar (GPR) data, verified by peat cores, has shown that data from simple depth probing are often inaccurate Parry *et al.* (2014). However, the high cost of GPR means that it has only been used in a small sub-set of studies - usually those requiring highly accurate morphology - which tend to be relatively localised (Warner *et al.* 1990, Theimer *et al.* 1994, Comas *et al.* 2005, Loisel *et al.* 2013). Thus, GPR is unlikely to provide a viable alternative to probing on a landscape scale. We believe that depth determinations from palaeoecological studies are considerably less prone to errors because a core is extracted and examined - especially as core stratigraphy is recorded and published, allowing peer evaluation of the data. If a core had terminated in an obstruction such as a wood layer and this became obvious when researchers examined it in the field, they would typically have attempted to continue coring to the true base.

c) Peat depth data from palaeoecological studies are often accompanied by supporting data which may be useful to researchers interested in carbon stocks. A large proportion of records will include detail on stratigraphy, which is potentially important because different types of peat (and non-peat sediments) have different bulk density, carbon and inorganic content. Many studies also include loss on ignition (ash content) data. Such data may be time-consuming to extract and compile, but can be highly valuable.

d) Many of the studies are old and the dataset spans approximately 100 years of measurements. Some studies, particularly those with an archaeological focus, were carried out prior to large disturbances such as peat cutting or the planting of forestry. These measurements offer an opportunity to study changes occurring over time and to investigate the effects of land management.

However, there are also important disadvantages to palaeoecological studies as a source of depth data:

a) Depths from palaeoecological studies are unlikely to provide an unbiased average depth for a site. Palaeoecologists will often have aimed to core the oldest part of the deposit, usually the deepest peat, often probing beforehand or selecting a site close to the centre of the bog in order to maximise the length and resolution of the sequence sampled. Smith *et al.* (2009) found that the ratio of maximum to mean peat depth was 2.16 on average, varying from 1.03 to 5.23. Therefore, if the deepest part of the bog was cored, the depth is likely to be a large overestimate of the mean value. However, this is not always the case, and cores are often taken opportunistically at locations at the edge of the mire that are easily accessible from roads or tracks. Information on how the coring site was selected is often lacking from publications, and the results of any depth probing in addition to the master core are often not presented. The data are likely to be accurate for specific coring points, but the representativeness of those coring points is uncertain.

b) As stated previously, many of the studies are old and it is possible that depth has changed since the measurements. While this may be a great advantage for some studies, it cannot necessarily be assumed that the measurements are representative of the contemporary situation.

c) Because data were not collected explicitly for this purpose, compilation is time-consuming and interpretation can occasionally be problematic. Sometimes there is ambiguity in determining what constitutes peat, or where precisely the base of the peat lies. A few studies have presented insufficient geographical information to allow the coring sites to be precisely located.

These limitations notwithstanding, we believe there is a strong case for the usefulness of palaeoecological datasets in this context.

INITIAL COMPILATION FOR SCOTLAND

To explore the potential of this data resource we produced a large compilation of data for Scotland through extensive searches of the palaeoecological literature. Our search criteria encompassed searches of literature databases, palaeoecological databases and previous compilations of the literature. Full details of the search approach are presented by Payne *et al.* (2016) but for this compilation we did not apply any restriction on date of publication or the presence of a chronology.

We identified depth information for 845 profiles in 437 sites from 158 publications (Supplementary Material 1). Most sites were represented by just a single measurement but we identified 21 sites with several (≥ 3) measurements. The sites are very widely distributed across Scotland with some data for all major peatland regions (Figure 1). Excluding sites where there was some uncertainty about depth, we calculated an overall (unweighted) mean site depth of 282 cm. A histogram of depth (Figure 2a) shows a modal depth category of 100–150 cm with a long tail of deeper sites. The deepest recorded peat depth is 980 cm for Danrigg Moss, a degraded raised bog (part of the Gardrum Moss complex) in the Central Belt of Scotland, south of Falkirk (Durno 1956). The dataset includes comparatively few (seven) sites with shallow peat < 50cm deep. Comparison with previous

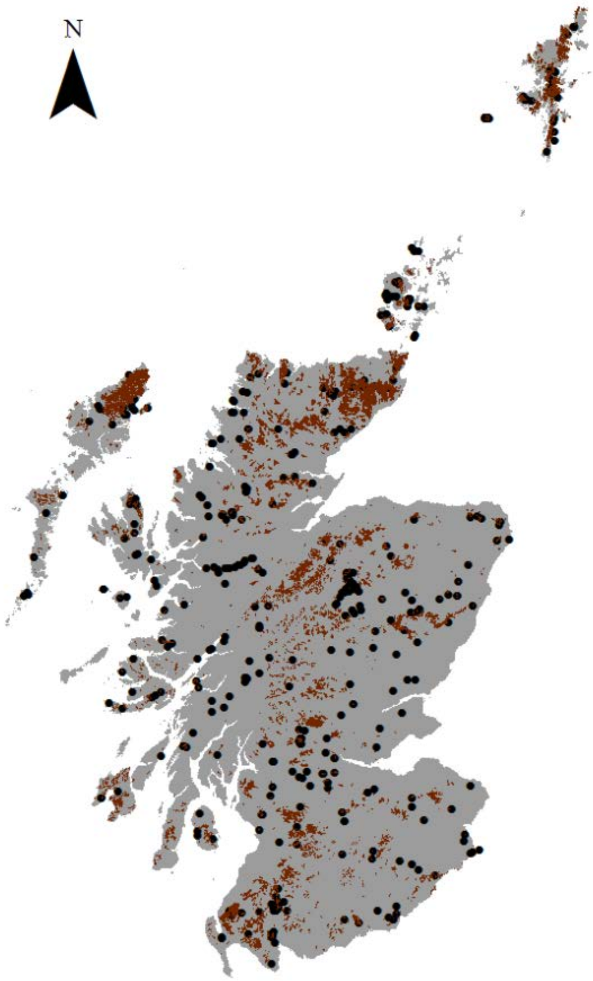

Figure 1. Map of Scotland (UK) showing the locations of sites with peat depth data from the palaeoecological literature (black filled circles). Brown polygons show areas recorded as predominantly peat in the 1:250,000 Soil Map of Scotland (MISR 1947–1981).

peat depth datasets, e.g. Chapman *et al.* (2009), suggests that such shallow peats are likely to be under-represented in our dataset as such sites are sub-optimal for palaeoecological research. The vast majority of sites in the dataset are classified as blanket bog, although the deepest sites are typically raised bogs (Figure 2b).

The dataset may be considered small for the extent of peatlands in Scotland (~ 1727 kha, Chapman *et al.* 2009), but it compares quite favourably with datasets previously used for carbon stock calculations. We compiled 845 depth measurements for Scotland, whereas only 302 measurements across all of Britain were used by Cannell *et al.* (1993) and Milne & Brown (1997). Our 437 Scottish sites compare against data for 278 sites used by Chapman *et al.* (2009), although the number of measurements *per* site was greater in that study (total n = 1455). Previous studies have generally not given full details of the locations of their depth measurements, but it is probable that our measurements are more widely distributed. For instance, the data of Cannell *et al.* (1993) were restricted to Forestry Commission land holdings.

The mean depth *per* site in our study (282 cm) is at the upper end of the range indicated by the literature. For instance, Cannell *et al.* (1993) used a figure of 243 cm and the same data were used by (Milne & Brown 1997) to calculate a weighted average of 280 cm. Chapman *et al.* (2009) calculated an area-weighted mean depth of 200 cm. Beyond the UK, the most cited paper on global peatland carbon stock (Gorham 1991) uses a mean depth figure of 230 cm. It is difficult to assess the representativeness of this mean depth for Scotland as our data are probably biased towards deeper peats while previous datasets are subject to differing and opposing biases, making it difficult to judge the direction of bias overall. It is probably reasonable to assume that true mean peat depth is less than 282 cm, due to the

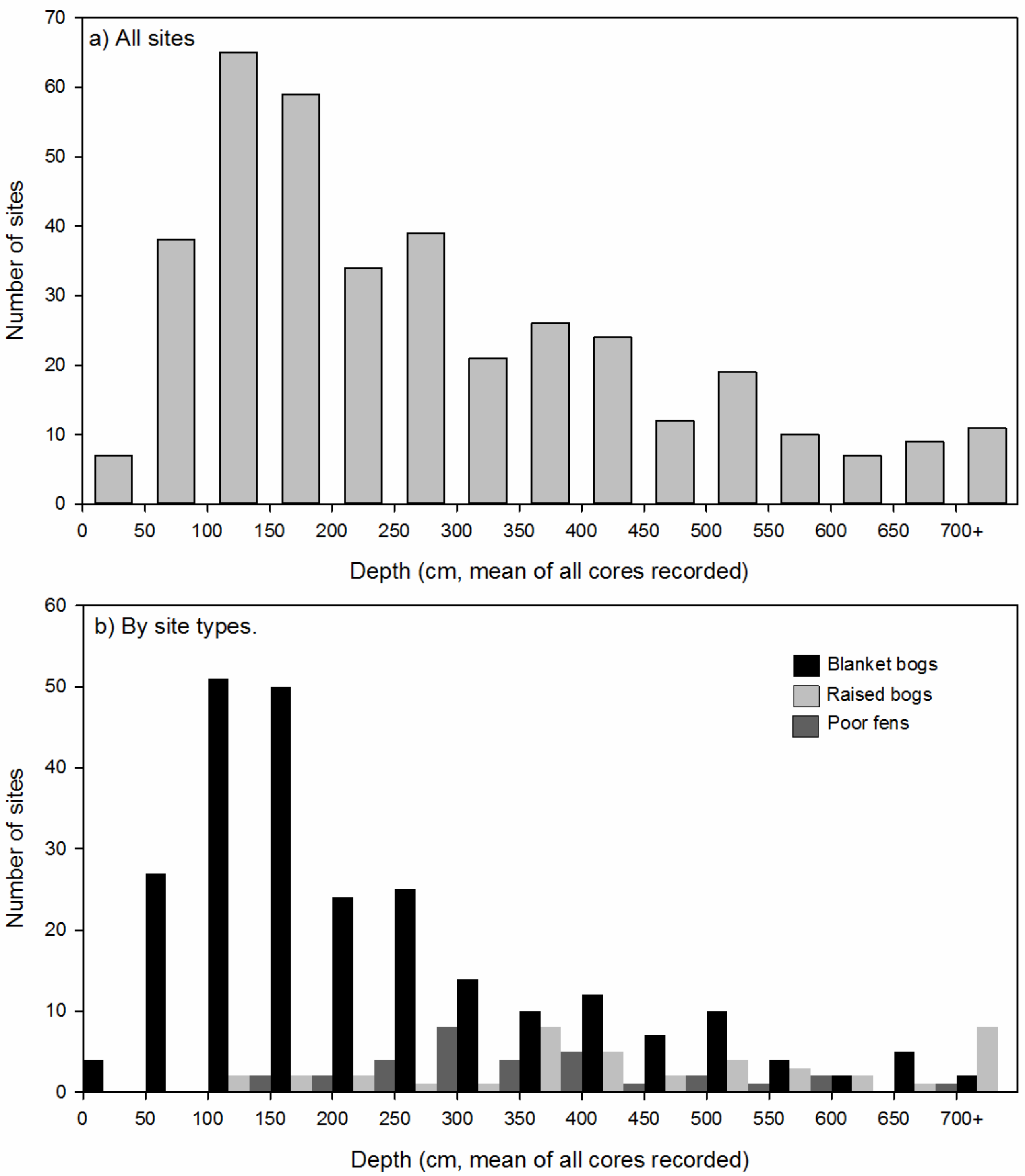

Figure 2. Peat depth from the palaeoecological depth dataset (Supplementary Material 1). A) All sites. B) Results broken down by site. Note that it was not possible to classify some peatlands on the basis of available information.

preference of palaeoecologists for deeper cores. Our mean site depth is considerably (41 %) deeper than that of Chapman *et al.* (2009). To place this disparity in context: if we re-scaled the carbon stock calculated by Chapman *et al.* (2009) to our mean site depth, this would imply an additional 660 MtC, equivalent to more carbon than is contained in all Scottish mineral soils (Bradley *et al.* 2005). Clearly, further work will be required to resolve this issue more satisfactorily.

Although we restricted our compilation to the depth of peat we note that the studies we reviewed demonstrate the frequent presence of carbon in deeper layers. In most sites of hydroseral origin peat is preceded by gyttja, lake mud or organic-rich clay which, while clearly not peat, will nevertheless contain considerable amounts of carbon. In sites that originated by paludification, buried mineral soils at the bases of the profiles may also contain considerable carbon (Moore & Turunen 2004, Fyfe *et al.* 2014). This deeper (buried) carbon is often overlooked in peatland carbon inventories. An initial estimate for Scotland was provided by Chapman *et al.* (2009) using data from Finnish and Canadian peatlands but is not yet supported by measurements. This topic deserves greater attention in the future.

CONCLUSIONS

While the representativeness of the locations of depth determinations from palaeoecological studies is uncertain and difficult to quantify, the data for those points are likely to be of generally high quality. Measurements for 437 widely distributed sites represents a considerable investment of time and money, which is unlikely to be matched by future studies. The limitations of other existing sources of depth data are also significant and we believe that depth data from palaeoecological studies should be integrated into future estimates of peatland carbon stocks. Due to their intrinsic biases it would not be wise to use these data alone. However, we envision that these data will be valuable to compare with, gap fill, verify and calibrate other datasets, particularly those which have extrapolated peat depth from measurements with restricted spatial distribution. Unless accurate depth measurements become possible by remote sensing, future studies will need to make the most of datasets which are currently available, accepting that they are often old and that all of them have limitations and biases. In this context we believe that measurements from palaeoecological studies are a potentially important component of the mix. Arguably, the best hope for better landscape-scale carbon stock figures is an improved mechanistic understanding of the factors controlling peat accumulation, and the development of models to allow depth (and ultimately carbon stock) to be predicted or interpolated from existing datasets.

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Supplementary Material: The Scottish Peat Depth Dataset.