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The historic peat record: Implications for the restoration of blanket bog (NEER011)

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The historic peat record: Implications for the restoration of blanket bog

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Cover photograph

Executive summary

Peaty soils such as those found in blanket bogs lay down a history of their vegetation composition, along with the relative humification of these remains, which can be used to reconstruct bog surface wetness. These records highlight the variability of vegetation cover over time at blanket bog sites and could therefore be used to provide context to inform targets for the outcome of any restoration work. Because the vegetation present currently or in the recent past on the surface of a bog might be due to a relatively recent change, a longer-term history would give a different baseline to aim for. This should be relatively easy to achieve at some level for sites that have had cores taken, for which a database already exists. Historical records show a general picture of natural cycles in peat wetness and vegetation cover, and highlight a large level of variability that is sometimes found over even quite small areas in the timing of peat initiation and the types of vegetation present. This local variability suggests that topography (which varies more within a small spatial extent than climate or edaphic conditions) is a strong determinant of peat growth.

However, climatic factors are also important. At some sites, past recovery of *Sphagnum* has been associated with wetter, cooler phases in the climate. Because rainfall and temperature are likely to change in future with continued climatic change, reconstructed climatic conditions at blanket peat sites could be used to determine whether the projected future climatic conditions at a potential restoration site are likely to fall within the range that supported peat formation in the past. This would help determine whether any restoration work has a chance of succeeding in the long term, and a database of sediment cores has been assembled for England that could be used as a starting point for this. One potential management strategy would be to accept that some vegetation that is currently considered undesirable has been present on blanket bogs in the past, and allow enough time and space for natural cycles to occur. However, what is not known is how much space would be needed to allow such natural cycles to continue, which sites are undergoing change as part of a natural cycle and which are not, or whether these natural cycles might be expected to continue in the same way in the future under climate change.

There is some evidence for human impacts on blanket bogs in the past; the use of marginal lands for grazing and agriculture appear to have stopped the spread of peat in some areas, and in some other areas deforestation by humans appears to have been instrumental in initiating peat production. This demonstrates that there is considerable potential for management actions to impact the character of blanket bogs – based on inductive reasoning it seems likely that the reversal of some negative factors (such as blocking drains and removing plantation forestry) will result in the restoration of hydrological function, which could drive further changes in vegetation away from dry heath and trees to *Sphagnum*-dominated blanket bog that actively forms peat. However, care should be taken when choosing species to re-vegetate bare peat, since *Calluna* is associated with drier areas. What is not currently known is whether this is a cause or effect of drier conditions, but it is possible that the introduction of *Calluna* to the bog surface might result in drying of the peat, which would slow the rate of peat formation. *Sphagnum* is associated with lower emissions of methane and is a main peat-forming species, so its suitability for re-vegetating bare peat is likely to be higher if it can become established.

The timing of the initiation of erosion at some sites is well before the nitrogen deposition that is often implicated in this, and erosion has not always been caused by human activity. Indeed, some bogs have switched between erosion and accumulation over time, and others have recovered naturally from human impacts. However, what makes some bogs more resilient than others or causes the switch between erosion and accumulation is not known, and further research here would be beneficial to inform restoration management.

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1 Introduction

1.1 Natural England (NE) commissioned this report into the palaeoecological literature in order to determine whether the management of blanket peat deposits, particularly blanket bogs, might be informed by the historical record contained within peat deposits. The overarching aims of this report are to determine whether palaeoecological information might be used to help determine where restoration might be most effective, where it might be feasible or unfeasible to restore peat given current or likely future climatic conditions and which management actions might be most effective for restoring function. Because the literature contains a lot of (often confusing) terminology, we begin here with a brief overview of some of this, as well as an overview of the methods used to study peat.

1.2 Waterlogged areas where peat develops because of very slow vegetative decay under aerobic conditions are called mires (Moor, 1986). Although there is a transition between the different types of mires, they can be classified in terms of the (i) origin of the mire and (ii) in terms of the water source at the time of the mire formation. For example, a "soligenous" mire forms as a result of water flow being impeded, whether on a valley side bounded by a water course at the lower end or in a gently sloping fen. A "topogenous" mire forms because of restriction of drainage due to a topographic feature, such as a basin.

1.3 The additional division of mires is based upon their source of water, for example "ombrotrophic" or "ombrogenous" mires receive nutrients solely from precipitation (rain and snow) rather than other sources such as runoff from higher slopes. They are consequently poor in nutrients (known as "oligotrophic") and have a low pH because of the low pH of rainwater. Only a few plants are adapted to these conditions, for example *Sphagnum* mosses. These act as a sponge, maintaining a high water level and sometimes producing a domed surface above the level of the surrounding ground (Moore, 1993).

1.4 The two major types of ombrogenous mire (colloquially known as bogs) in Britain are raised mires and blanket mires (Moore and Bellamy,1974) but alternative classifications and transitional types have been described (e.g. Goodwillie, 1980). In blanket mires (blanket bogs), peat formation is not confined to basins and lowland areas but spreads to sloping terrain (Lindsay,1995). Peat in blanket bogs forms by paludification, the formation of peat directly over a soil or rock surface where climate conditions allow. This is in contrast to terrestrialisation, which describes the infill of small lakes, followed by development of fen vegetation and eventually the formation of a raised bog.

1.5 Peatlands are unique in that they are the only plant community to lay down *in situ* a detailed record of their own history in the form of partially decomposed plant remains (e.g. Birks 1975), with older material further below the surface. They are, therefore, an important palaeoecological resource. Blanket peats can be sampled by palaeoecologists using a coring device or by taking a sample from a section using a box sampler such as a rectangular tin. There are very few sites that can be sampled using only one of these methods. The sampling method is usually based upon whether there is a suitable section (deep enough to represent the entire record of the peat deposit) and whether this section is in the deepest part of the blanket bog (if a long chronology is required). Probing can be used to establish an approximate morphology of the blanket peat base and subsequent cores taken from the deepest part of the bog.

1.6 The records often show that peat bogs are in a constant state of change, depending on climatic, edaphic and topographic factors. These records have the potential to inform the current management of blanket bogs and provide important context in determining the desired outcome of any management actions. In order to facilitate such work, NE commissioned this report to give an overview of palaeoecological studies of peatlands and their bearing on current management practices. As Birks (1996) states "Palaeoecology can be used to assess the presumed naturalness of mires by detailed examination of the stratigraphy of the underlying peat and its contained pollen content". Fragility of an ecosystem equates with inherent sensitivity to damage and it may increase as land-use pressures intensify or as pollution increases (Ratcliffe, 1977).

1.7 In this report, we present an overview of the palaeoecological literature, structured around the following questions:

1) What are the climatic conditions required for peat formation?
2) Which species are involved in peat formation? Are these consistent across space and time?
3) Which locations have a long history of peat formation?
4) Which factors affect blanket bog erosion?
5) What is the impact of management/restoration on blanket bogs?

1.8 The answers to these questions could inform management and restoration attempts by highlighting where restoration might be most effective both in the short term and the longer term (in conjunction with climate projections). They could also help with setting targets for restoration and inform which species are most suitable for particular sites.

2 Research methods

2.1 To give an overview of the palaeoecological literature, we performed a Rapid Evidence Assessment (UK Government Civil Service, 2010). We searched the scientific literature using 'mySearch', Bournemouth University's resource discovery tool, which is hosted in EBSCO's Discovery Service. mySearch searches all the traditional bibliographic databases to which Bournemouth University subscribes (including Scopus, Web of Knowledge (including Science Citation Index), Environment Complete, CAB Abstracts, Academic Search Complete, MEDLINE Complete, GreenFILE, ScienceDirect, JSTOR, Hospitality and Tourism Complete, Business Source Complete, Publisher Provided Full Text Searching File, BioOne Online Journals, OAIster, British Library Inside Serials & Conference Proceedings and British Library EThOS), in addition to extensive journal publisher feeds and peer-reviewed open access sources. We also searched Google Scholar because it returns results from a range of grey literature and books, as well as including papers as soon as they are available online and so returns the most recent advances. The date searches were performed and search strings used are shown in Table 1. For the Google Scholar searches a large number of results were returned, so the results were ordered by relevance and the first 100 hits were screened from each search.

2.2 Screening took place initially at the title level (176 of 359 sources were rejected at this stage), with articles passing this stage being further screened for relevance at the abstract level (see Appendix 1 for details). The search and screening was carried out by Dr. Binney, with supervision of search terms by Dr. Stewart and 10 % of hits being additionally screened at the title and abstract level by Dr. Gillingham to ensure no bias was introduced. The kappa test (see Collaboration for Environmental Evidence 2013) was used to measure the level of agreement between reviewers as to the papers to be included or rejected, with a value of 0.727 obtained for the 10 % included in this sample, indicating 'good' agreement. Full-text of the sources selected for inclusion was then sought, with any failures to obtain full-text sources or to utilise full-text sources due to language barriers recorded in Appendix 1. This screening and selection process resulted in 68 papers from the scientific literature being read at the full text level of which 28 were included in the final report. Further papers were included after consulting the references in these sources, as well as expert knowledge from the project team. In addition, previous reports produced by Natural England were consulted (e.g. Shepherd *et al*., 2013) and literature known to Natural England or the authors that would not be present yet in searchable databases was also included where relevant (e.g. Blundell & Holden 2015, Suggitt *et al*., 2015).

2.3 The quality of selected sources was assessed on a scale of 1-5 (see Appendix 2) on the following criteria; Selection bias (the presence of appropriate controls), Measurement Bias (whether knowledge of the treatment could influence measurements), Detection bias (accuracy and repeatability of measurements) and potential for future use (i.e. whether data was included that could be used to parameterise models predicting the likely effectiveness of management actions).

Table 1 Details of the searches carried out to return literature for this report. 246 papers of those returned here were unique hits, i.e. only returned by one combination of terms across both mySearch and Google Scholar

Database	Search string (* wildcard)	Number of hits	Date of search
mySearch	blanket bog AND palaeoecology	4	21/10/2014
mySearch	blanket bog AND pollen	19	21/10/2014
mySearch	blanket bog AND palynology	4	21/10/2014
mySearch	blanket bog AND plant macro*	4	21/10/2014
mySearch	blanket bog AND climate change	20	21/10/2014
mySearch	blanket peat AND palaeoecology	24	21/10/2014
mySearch	blanket peat AND climate change	47	21/10/2014
mySearch	blanket peat AND plant macro*	7	21/10/2014
mySearch	blanket peat AND palynology	10	21/10/2014
mySearch	blanket peat AND pollen	71	21/10/2014
mySearch	upland peat AND Holocene	3	21/10/2014
mySearch	blanket peat AND Holocene	37	21/10/2014
Google Scholar	blanket bog AND palaeoecology	407	03/11/2014
Google Scholar	blanket peat AND palaeoecology	509	09/10/2014
Google Scholar	blanket peat AND palynology	339	09/10/2014
Google Scholar	blanket bog AND plant macro*	123	10/10/2014
Google Scholar	blanket bog AND climate change	1860 (60 only)	10/10/2014

3 Results of literature review

What are the climatic conditions required for peat formation?

3.1 Lindsay *et al*., (1988) reviewing other literature, identified four climate conditions necessary for peat formation:

1) >1000 mm rainfall
2) >160 wet days (>1mm rain)
3) mean temperature of <15 degree C for the warmest month
4) minor seasonal fluctuations in temperature

The initiation of blanket bog accumulation

3.2 Areas of blanket bog accumulation are mainly in the high latitude oceanic regions such as Tierra del Fuego and the Falkland Islands in the southern hemisphere and Norway and the British Isles in the northern hemisphere. In the British Isles, blanket bogs are common in northern England, north and west Scotland and western Ireland. To better understand the long term stability of a blanket peat complex we need to look at the conditions necessary for peat initiation as well as examine evidence of erosion and degradation. Peat accumulates in a range of situations and there are a variety of causes. Ombrotrophic mires require high rainfall, hence their concentration in hyper-oceanic areas of the world. However, there is still debate in the palaeoecological literature over the causes of peat initiation, particularly for blanket bogs.

3.3 The generally accepted hypothesis for peat initiation and development is that peat spreads outwards from "initiation foci" located in basins, lowland and plateau areas (e.g. Edwards and Hirons,1982; Chambers,1984; Moore *et al*., 1984; Tallis, 1991). The basin peats are often characterised by the presence of "fen" communities at the base of the profile (corresponding to terrestrialisation) and valleyside peats usually form by direct paludification (peat formation directly on the minerogenic substrate).

3.4 The origin and development of blanket mires (or peat initiation) has been interpreted as resulting from deforestation (Moore, 1973), progressive paludification (peat formation on bare soil or rock, Taylor and Smith, 1980) and climatic deterioration (a change to cooler and/or wetter conditions, Godwin, 1946). Peat initiation and formation is also strongly controlled by site topography (drainage must be impeded for peat formation) and the effective rainfall precipitation/evaporation ratio. In very wet areas of acidic rocks, the soil nutrients can leach out and the minerals are redeposited lower down as an iron pan, which can impede drainage. This encourages the growth of bog vegetation species (for example *Sphagnum*) and the bog begins to grow. Commonly, macrofossils shrubs and trees are found at the base of blanket peat exposures which represent drier conditions before the initiation of peat accumulation. In Ireland, there is evidence for human activities (for example deforestation) causing the soil fertility to deteriorate, allowing bog to develop (Birks & Birks 1980).

3.5 There have been a wide variety of radiocarbon age estimates obtained for peat initiation within relatively local areas in the South Pennines (Tallis, 1991), Mid Wales (Smith and Taylor, 1989) and Northwest Scotland (Moore *et al*., 1984), so some sites started accumulating peat much later than others even within suitable regional climatic conditions. This is because a threshold of moisture retention must be reached for accumulation to begin, and subsequent spreading of blanket peat takes time, leading to these different basal dates. The timing of the initiation and the spatial and temporal patterns of blanket peat development are not yet fully understood, principally because of the large number of variables associated with peat formation (e.g. topography, hydrology, climate, soils). However, radiocarbon dating is expensive, and a comprehensive investigation of both initiation and patterns of spread has yet to be done at a large scale as it would require a large number of such age determinations.

3.6 Deeper, older bogs, for example those in the Pennines, show initial peat growth during the 'Atlantic date' (approximately 8300 to 5750 years ago) when the climate was thought to be wetter and warmer than present. Conway (1954) concluded that the growth of peat was therefore driven by climatic conditions. However, with the advent of radiocarbon dating and the development of pollen analysis, human impact was linked with peat bog growth (Moore, 1973, 1975). Moore concluded that the pollen diagrams of shallower peats on sloping ground from a variety of areas (such as the Pennines, the Lake District and Central Wales) suggested their formation began during the latter part of this time, often about the time of the elm decline (approximately 6300 to 5300 years ago), rather than as soon as climatic conditions were suitable. Moore therefore proposed that peat initiation and accumulation was associated with the beginning of more intense human impacts during the early Neolithic. Trees remove water from a bog through evapotranspiration. Moore's study of the pollen evidence at UK sites showed that there were a series of disturbance phases to the woodland, which would reduce evapotranspiration and hence raise the water table. The woodland recovered, but successive disturbance through clearance, grazing and fire eventually led to development of *Sphagnum* peat. Moore (1973, 1975) concluded that the clearance of the forest caused the development of the peat.

3.7 However, there is evidence from other areas, for example the Pennines, which shows that forest continued to exist well after peat formation (Tallis, 1975) and in South Wales, Chambers (1981, 1982) showed that the timing of peat development was more varied. Smith and Cloutman (1988), also working in South Wales, showed that the dates of peat initiation within a very local area (8 ha) spanned a period of over 4000 years (approximately 8900 to 4500 years ago). The evidence for human causes was based on the presence of charcoal fragments at the base of the peat profiles which they concluded was from early human forest clearance.

3.8 Tipping (2008) looked at the palaeoecological evidence at five sites in Scotland for the timing and spread of blanket peat bogs, in a study representing the synthesis of 10 years of work. Very few investigations have described peat development in space as well as in time, another is Tallis (1991) in the southern Pennines. Tipping (2008) showed using geomorphic, stratigraphic, palaeoclimatic, palaeoecological and radiocarbon dating evidence that blanket peat was common or abundant over much of the highland landscape within a few thousand years of the beginning of the Holocene period (approximately 11,700 years ago) There was no evidence from the fossil pollen records for significant disturbance preceding the initiation of peat accumulation. Similarly the charcoal record did not indicate burning before peat initiation. There was no conclusive evidence for factors controlling blanket peat spread or even why it spread. Tipping (2008) suggests that small hollows may be the foci for peat initiation and subsequent spread. There was no evidence that blanket peat developed as a result of anthropogenic activities. Indeed, the evidence suggests that farming communities successfully resisted the natural spread of peat across their fields by farming the marginal land at the edge of the bog and using it for grazing purposes. Tipping (2008) concluded that peat initiation has different causes at different locations but the cool and wet environmental conditions necessary for peat accumulation excluded other ecosystems.

Categories of blanket bogs

3.9 Based on topography and hydromophology, Lindsay (1995) divides blanket mires into six sub-categories (watershed mire, valleyside mire, spur mire, saddle mire, eccentric mire and unconfined raised bog units, see Figure 1). These classes are not absolute and some mires may exhibit characteristics of more than one of these types. However, the divisions form a useful tool for the categorisation of sites, and provide a system to test the relative sensitivity of different site types for recording changes in the degree of humification (the decomposition of plant material) (*sensu* Chambers, 1984).

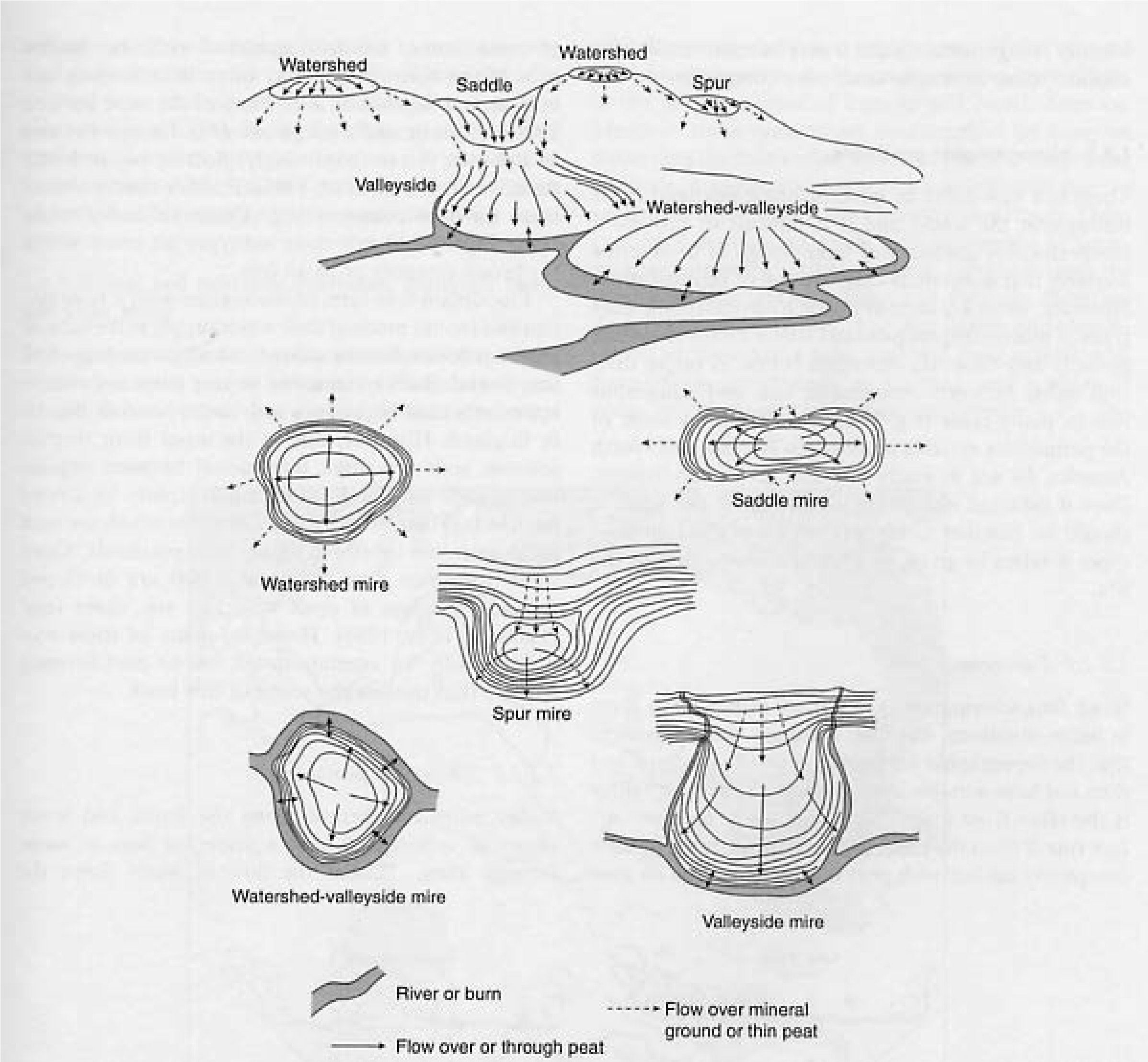

Figure 1 Subcategories of blanket bogs according to Lindsay (1995). Redrawn by Charman (2002)

Watershed mire

3.10 This type of mire is formed on plateaus and ridges where the ground slopes away on all sides. Since the only source of water is directly from precipitation, watershed mires are clearly ombrotrophic. These mires are very important for palaeoecological investigations as the peat growth is directly linked to precipitation with no other inputs of moisture. Because of this, the degree of peat humification is directly linked to changes in precipitation and has a better climate signal than in mires that experience rainfall runoff from higher ground.

Valleyside mire

3.11 This type of mire is formed on gently sloping or almost level ground, where the downslope margin is bounded by a river or water body and the upslope margins may be influenced by water seepage from the slope above. These mires often have their crown close to the upslope margin. If a single mound of mineral ground bounded on all sides by streams, is covered by peat which is both of watershed and valleyside mire types then this is categorised as a watershed/valleyside mire type.

Spur mire

3.12 Spur mires occur on broad spurs where the lower edge of the mire is not bounded by a river or water body but is delimited by a steepening slope. The upslope margins may be influenced by seepage water from the slope above.

Saddle mire

3.13 Saddle mires occur on depressions (cols) between two higher slopes which may be a source of water seepage to the mire. The mire is largely ombrotrophic if the adjacent higher ground slopes gradually upwards from the col. The downslope margins are at right angles to the upslope margins, and the downslope margins are bounded by increasing steep slopes.

Eccentric mire

3.14 These are found on slopes where the peat forms a dome and where at least one axis slopes continuously from an upslope edge, corresponding to the highest part of the mire, to a downslope limit. The surface of the mire is intensively patterned with different stands of vegetation and pools.

Unconfined raised bog units

3.15 These occur where a blanket mire complex forms a dome of peat accumulation (i.e. transforms into a raised bog) which is not confined by the contours of the underlying terrain. When a certain peat depth is reached, the bog is not controlled by the underlying topography.

3.16 To conclude, blanket peat is found in upland areas with high rainfall. Blanket peat initiation and growth occurred throughout the Holocene as a result of natural processes of acidification and leaching (Bennett *et al*., 1992) and also as a result of human activities such as forest clearance and grazing. Indeed, within a relatively small spatial area, peat initiation and growth rate can be seen to vary and depend more strongly on topography than climatic and edaphic conditions. The geographical spread of blanket peat has also been hampered by humans in the past, by exploitation of the marginal land at the edge of the peat bog for agriculture and grazing which restricted further expansion.

Which species are involved in peat formation? Are these consistent across space and time?

3.17 The principal feature of mire vegetation is the dominance of acidophilous plants such as *Sphagnum* spp., *Erica tetralix* and *Eriophorum augustifolium*. Drier parts of the mire surface are characterised by a greater abundance of vascular plants such as *Calluna vulgaris*, *Eriophorum vaginatum* and *Scirpus cespitosus*. Whilst *C. vulgaris* can grow in virtual monocultures, it only forms peat in the presence of wetland plants such as *Sphagnum* and *Eriophorum*, although there is some evidence that *Molinia* can form peat on its own (Shepherd *et al*., 2013). Mire vegetation communities have been described by a number of authors (e.g. McVean and Ratcliffe, 1962; Ratcliffe, 1964; Good and Ratcliffe, 1977; Lindsay *et al.,* 1985; Rodwell, 1991) and a summary is presented here.

3.18 Peat landforms can be investigated at different spatial scales. The macrotope is defined as “the geotope that has been formed by the fusion of isolated mire mesotopes” (Ivanov 1981). The mesotopes are isolated mire massifs (e.g. watershed mire or spur mire) and a microtope is “the part of the mire where the plant cover and all other physical components are uniform” (Ivanov, 1981). The description of vegetation of a mire therefore depends which spatial scale is of interest. Blanket mires do not have a uniform surface and are composed of mounds, hummocks, ridges and pools. The vegetation community on each of the ‘microforms’ is distinctive and different. For example, *Eriophorum* (cotton grass) and *Sphagnum* mosses are found on ridges whereas the adjacent pools maybe locally colonised by *Scheuchzeria palustris* (Rannoch rush).

3.19 The microforms are divided into two zones, terrestrial and aquatic (Lindsay *et al*., 1988). The National Vegetation Classification (NVC) of bog communities and sub-divisions within the microforms mire margin and smooth blanket mire includes 29 NVC categories. Plant species involved in peat formation can change within relatively local areas within a blanket bog.

3.20 There are essentially two types of bog in Britain raised bog and blanket bog (Goode & Ratcliffe, 1977) with a transitional (intermediate) between the two also occurring (Hulme, 1980). Sites are usually assigned to one or two of the main types of bog and the distribution of microtope zones between types is indicative rather than absolute (Lindsay, 1995). Within blanket bogs, as explained earlier, there are mesotope type bogs (watershed, spur, valleyside, watershed/valleyside and eccentric), each with microtopes of terrestrial and aquatic zones. Raised bogs and blanket bogs, therefore, represent the end-points of an ecological continuum, although sites usually fall within the two main types. Bogs are dynamic, complex ecosystems and mesotope types merge at boundaries.

3.21 The main peat forming species are *Sphagnum* mosses. These species often have overlapping ecological niches and occupy a range of water-table related habitats. There are hummock/high ridge species (e.g. *Sphagnum imbricatum*, which is now known as *Sphagnum affine*), low ridge species (e.g. *Sphagnum papillosum*) and those found in hollows (e.g. *Sphagnum cuspidatum*) and pools (e.g. *Sphagnum auriculatum*).

3.22 The main peat forming plant species over the Holocene have been:

Sphagna

- *Sphagnum magellanicum* – found on growing and mature hummocks (**main hummock builder)**
- *Sphagnum rubellum* – found on growing and mature hummocks (**main hummock builder)**
- *Sphagnum papillosum* – (main hummock builder)
- Sphagnum subnitens (formerly S. plumulosum – (**main hummock builder)**
- *Sphagnum fuscum* – hummock builder,
- *Sphagnum* affine (formerly S. imbricatum) – hummock builder
- *Sphagnum cuspidatum* – found in pools. Submerged or half submerged diffuse green mats occupy the raised bog pools
- *Sphagnum subsecundum* – found in pools (usually associated with eutrophic habitats)

- *Eriophorum vaginatum* (cotton grass) (Cyperaceae)
- *Molinia caerulea* (purple moor grass) (Poaceae)
- *Scirpus caespitosus* (deer grass) (Cyperaceae)
- *Rhynchospora alba* (beaked sedge) (Cyperaceae) (**emergent surface vegetation)**
- *Racomitrium lanuginosum* (moss) Grimeaceae) (**associated with haggs)**
- *Calluna vulgaris* (ling) (Ericaceae) (**includes decaying hummocks and haggs)**
- *Erica tetralix* (cross leaved Heather) (Ericaceae)
- *Narthecium ossifragum* (yellow bog asphodel) (Nartheciaceae) **(found in pools)**
- *Pedcularis palustris* (marsh lousewort) (Orobanchaceae – previously Scrophulaceae)
- *Menyanthes trifoliata* (bog bean) (Menyanthaceae)
- *Drosera* spp. (sundews) **(found at the margins)**
- *Pinguicula vulgaris* (butterwort) (Lentibulariaceae)

3.23 *Sphagnum* macrofossils can be used to reconstruct past Bog Surface Wetness (BSW), (Barber, 1981, 1993, Barber *et al*., 1994, 1999) and show changes in mire conditions. Other macrofossils and fossil pollen and spores can be used to reconstruct the peat forming vegetation and the vegetation surrounding the bog. The *Sphagnum* macrofossil record is slightly complicated by competitive factors between species and human disturbances rather than climate change factors. For example, *Sphagnum imbricatum (affine)* was once abundant at Butterburn Flow in Northern England (McClymont *et al*., 2008). Its replacement by *S. magellanicum* did coincide with an increase in bog wetness, but *S. imbricatum* had survived such fluctuations in wetness prior to its eventual decline around 1300 AD. However, increasing human disturbance surrounding the bog at this time may have led to increased nutrient inputs, which combined with the increased wetness may have reduced *S. imbricatum*'s competitive ability.

3.24 The nature of blanket peats and their constituent microforms means that analysis of proxy environmental data can be complex. Despite this, detailed proxy-climate records have been obtained from blanket bogs. Visual inspection of peat stratigraphy, on the basis that the lighter (less humified) and darker (more humified) layers represented wetter and dryer conditions, respectively, as one of the earliest methods to sub-divide the Holocene (Godwin, 1975). One method of assessing the degree of humification is to make an alkaline extraction of the peat (using sodium hydroxide) and measuring the amount of light that passes through this extraction using a spectrophotometer. The less humified a peat sample is (less broken down) the more light will pass through the extraction (higher transmission values). This provides a relative measurement of the degree of humification (Blackford & Chambers, 1993). This method is relatively fast and easy and produces high temporal resolution records of peat humification over long time periods, for example a sequence across 5,500 years from southern Scotland (Chambers *et al*., 1997) with a core depth of 120 cm could be resolved to around 25 years per sample, giving an idea of the environmental conditions in 25 year time slices over 5,500 years. The changes in humification provided by such studies provide important context of the differing environmental conditions that support peat formation and how bogs can change under natural environmental variations. This is important as it could be used to determine whether the climate at a potential restoration site is likely to remain within the limits that have supported peat development in the past at that site. Equally, this contextual information could inform whether the surface of the bog might naturally be expected to change under different environmental conditions, helping to predict what the expected outcome of a restoration attempt might be.

3.25 Barber *et al*., 1999, analysed plant macrofossils from Moine Mhor, a water-shedding blanket bog at 920m altitude in the Cairngorms. The series of light and dark bands in the peat at this site was found to be replicable over an area of 20 x 30m, which indicates a climatic driver of humification rather than local hydrological changes. This was confirmed in the laboratory using humification and bulk density analyses. The peat sequence at Moine Mhor included layers of relatively well preserved plant remains (macrofossils). This plant macrofossil data supported the humification evidence, indicating relatively wet episodes with a high proportion of *Sphagnum* remains and drier episodes which were dominated by *Racomitrium.*

3.26 The evidence for wet and dry episodes from the peat at Moine Mhor is extremely valuable because there was a wet shift during the Little Ice Age (approximately 1650-1850 AD). This wet shift matches a similar shift identified at a lowland raised bog in Northern Ireland (Barber *et al*., 2000), approximately 300 miles away and with a 900 m difference in altitude. This demonstrates parallel responses to climate forcing (i.e. bogs in difference places responded in similar ways to changes in climate) and reinforces the importance of blanket bogs as archives of past climate.

Which locations have a long history of peat formation?

3.27 Blanket bogs can develop over a landscape on slopes less than about 15º (Birks & Birks, 1980) in areas of high rainfall (see above) and become relatively independent of the natural drainage patterns because as they accumulate they can become detached from the underlying topography (Moore *et al*., 1991). Moore & Bellamy (1974) suggest that blanket peats can form on slopes up to 25º.

3.28 In England, blanket bogs are found in upland areas with high rainfall across a large proportion of the year, and relatively low temperatures with low seasonal fluctuation (see section 4.1).

3.29 The main areas of blanket peat formation (see Figure 2) are:

- Northumberland
- North Pennines
- North Yorkshire Moors
- Lake District
- Forest of Bowland, Lancashire
- South Pennines
- Yorkshire Dales and Nidderdale
- Peak District
- The Black Mountains
- Exmoor
- Dartmoor
- Bodmin Moor

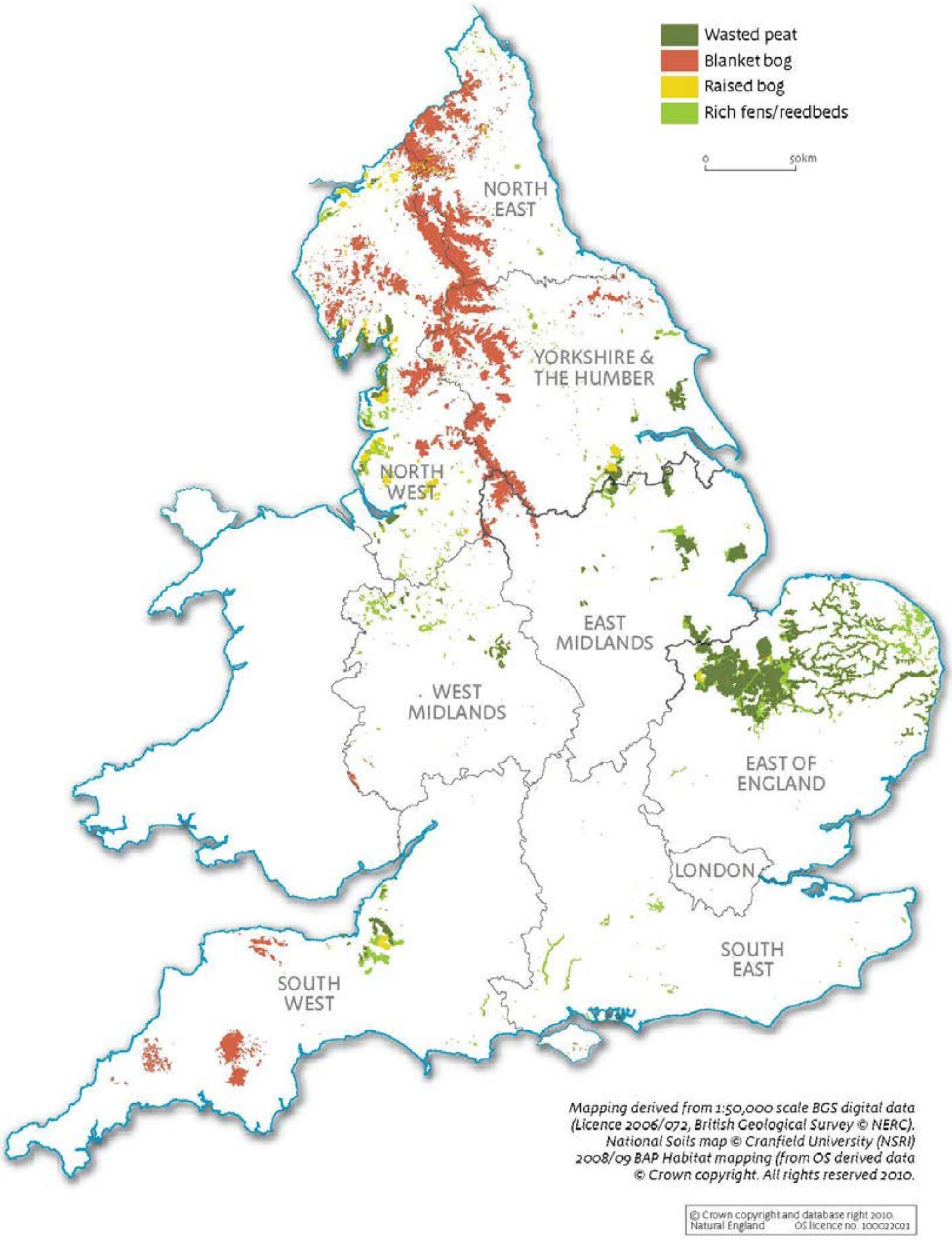

Figure 2 The location and extent of blanket peat (shown in red) in England (from England's peatlands: carbon storage and greenhouse gases, Natural England publication 257)

3.30 A selection of palaeoecological investigations into blanket bog sites in the UK is summarised below, demonstrating the valuable palaeoecological resource these bogs represent. These sites represent examples from some of the blanket bog regions listed above. They generally arose from the search engines and background reading. All but one (Blundell & Holden 2015) are classic studies in the palaeoecology of blanket peat bogs. Blundell & Holden (2015) has been included as an example of a palaeoecological study initiated specifically to inform site management and therefore has a different aim to the others. A database of 763 coring locations in England (most but not all from areas of blanket bog) has been compiled elsewhere (Suggitt *et al*., 2015) and this could be used as a basis for modelling suitable conditions for peat formation in more detail, creating a database such as this for Wales and Scotland would increase the utility of any model.

Radiocarbon Dating

Many of the studies listed below make reference to ‘radiocarbon years’, so we give a short explanation of the process here. Radiocarbon measurements are reported in years before present (BP). For standardisation reasons, “present” is 1950 on the assumption that atmospheric radiocarbon has been approximately constant since then. The advantage of using a fixed date is that the year the radiocarbon age was measured is not important.

The concentration of radiocarbon in the atmosphere has changed over a longer time period. Therefore if the concentration of radiocarbon in a sample is measured and a half-life assumed of 5730 years (the recorded amount of time for half the radiocarbon concentration in a sample to decay), a radiocarbon age can be reported.

The atmospheric concentration of radiocarbon has been measured using tree rings, the exact age of which is known. These tree rings provide a method for calibrating radiocarbon years and calculation of the calendar year.

Allt Na Feithe Sheilich, Monadhliath Plateau, Scotland

3.31 A particularly important blanket peat site is Allt na Feithe Sheilich on the Monadhliath Plateau in Central Scotland. The site is located within a large blanket bog that is being eroded by a stream. The erosion gulley was sampled and investigated by Hilary Birks as part of her PhD (Birks, 1969) and subsequently published in 1975 (Birks, 1975).

3.32 This site is important as it is one of the oldest blanket peat profiles in the UK (it dates back to the Late Devensian/Holocene boundary, approximately 10000 years ago) and has consequently been the subject of several separate investigations. The site was first investigated by Lewis (1906) who recorded two layers of pine stumps overlying a layer of birch macrofossils at two sections and one layer of pine stumps overlying birch wood at a third section taken at a different part of the site. Samuelsson (1910) subsequently only found one band of pine stumps from this section, which was confirmed by Birks (1969, 1975). Birks (1969, 1975) describes the peat stratigraphy, the wood remains and analyses the pollen preserved within the peat. Figure 3 shows the pollen diagram and stratigraphy from this site. The lowest 1.3 m of peat is humified, with frequent occurrences of birch and willow wood fragments. Above this are large, well preserved pine stumps, which are overlain by humified *Sphagnum* peat containing *Calluna* fragments and a layer of birch wood. The pollen evidence indicates that before 9400 before present (BP, radiocarbon years), birch-willow-juniper scrub with herbs was widespread. After 9400 BP, birch woodland with some willow and hazel became established and pine migrated to the region about 7500 BP. The pollen and macrofossil evidence shows that the local vegetation changed to a drier, more acid *Calluna-Empetrum* bog at this time, allowing pine to invade. Subsequently at 6900 BP the bog became wetter, causing the death of the trees (hence the preserved pine stumps) and the development of a *Sphagnum-Calluna* bog. At about 4400 BP, the bog once again became drier, allowing some birch to grow locally (hence the upper layer within the peat). In about 4000 BP there was a widespread decline in Pine, thought to be due to a downturn in climate (i.e. a change to colder, wetter conditions).

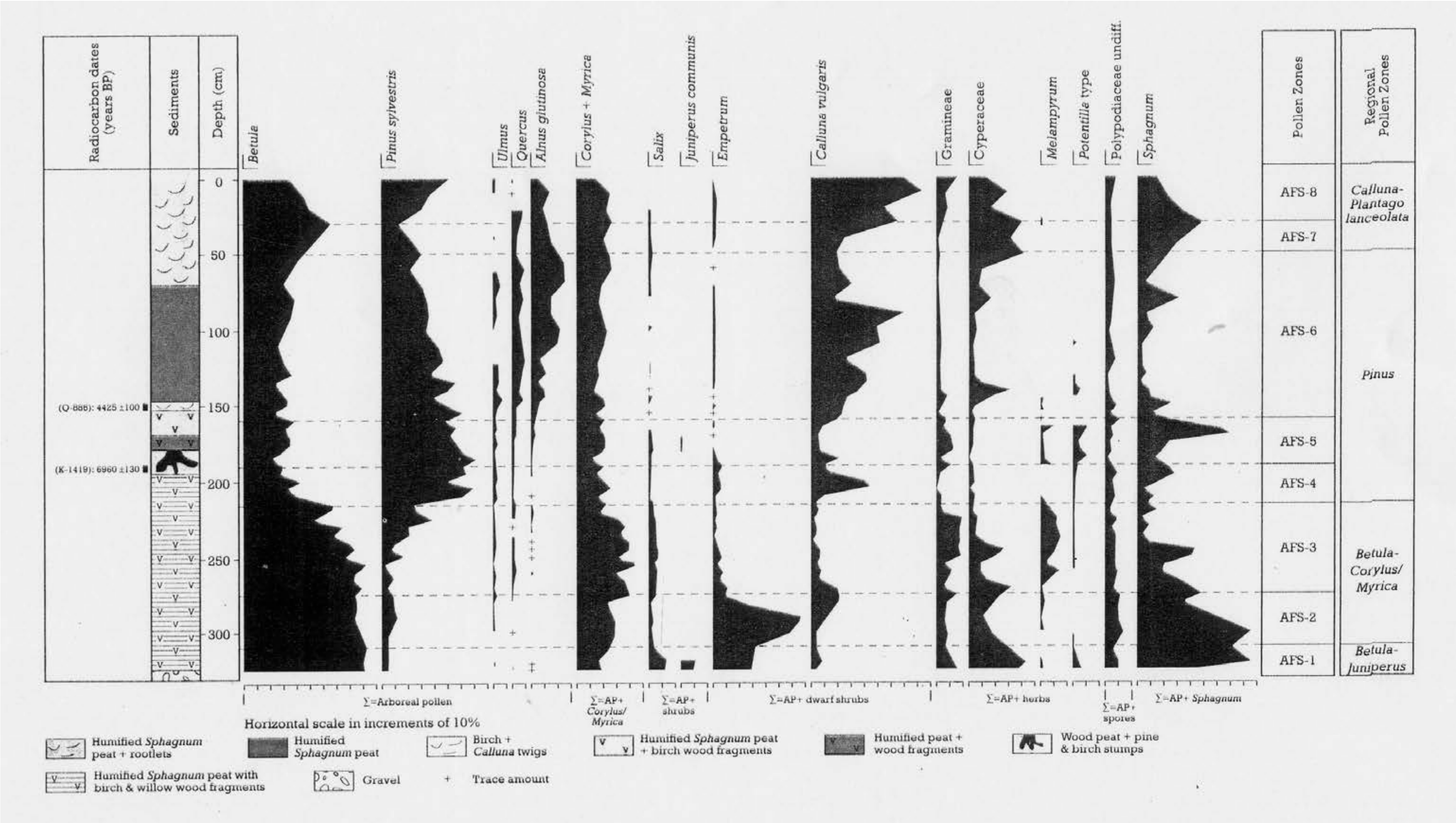

Figure 3 Relative pollen diagram from Allt na Feithe Sheilich, showing selected taxa as percentages of the pollen sums indicated (from Birks, 1975)

3.33 Allt na Feithe Sheilich is important because it is records perhaps the earliest development of blanket bog in the UK (Birks, 1980) and the natural establishment and demise of pine at the site. Sub-fossil pine stumps preserved within blanket peat are frequent in Scotland. Lewis (1906) assumed the pine stumps across Scotland were the same age, but radiocarbon dating has demonstrated that the ages differ considerably in the Cairngorms (Birks, 1975) and on Rannoch Moor in western Scotland (Bridge *et al*.,1990). The wide ranging ages indicates that there was no one factor that controlled the growth of trees on the blanket bog but possibly that small climate fluctuations affected the vegetation at each site in different ways. Differences in altitude, hydrology, aspect and topography resulted in some sites becoming favourable for the establishment and growth of trees whereas others did not. The death of the trees at Allt na Feithe Sheilich was due to an increase in wetness (Birks, 1975), although not necessarily because of changes in climate, since McVean (1963) showed that one single wet season may be sufficient to kill trees growing in marginal locations such as a blanket bog.

3.34 The completeness and length of the record at Allt na Feith Sheilich makes this site extremely important in the vegetational history of the Cairngorms. It is at a relatively high altitude (600 metres above sea level) in comparison to other sites in the region and it is one of the most important sites in Scotland for its record of Holocene environmental and vegetation change in an upland area. This site demonstrates the value of an archive of proxy evidence for local and regional environmental and climate change, and that blanket peat bogs change considerably under natural environmental conditions. Although they are often described as "sensitive", blanket bogs have been shown to exist and accumulate over thousands of years despite changes in surface vegetation and surface wetness. However, this site is currently being eroded by the headwaters of Allt na Feithe Sheilich, demonstrating that such archives are not guaranteed to be permanent.

Round Loch of Glenhead, Scotland

3.35 This is a small lake at 300m in Galloway, which was investigated by Jones *et al*., (1989). It was surrounded by mixed woodland (*Quercus, Alnus glutinosa, Ulmus, Corylus avellana* and *Pinus sylvestris*) until about 5500BP (radiocarbon years). Blanket mires and *Calluna* moorland increasingly replaced woodland until about 2000 years ago, when the blanket moorland and *Calluna* moorland of today was formed. Many of the blanket bogs in this area are currently suffering from severe erosion. The history of this erosion is recorded in the lake sediments by the changing amount of organic material in the sediments (Stevenson *et al*., 1990). Between 1500 and 1700 AD, there was an increase in organic material in the sediments, caused by input of eroded peat into the lake. The cause of this extensive peat erosion is not yet resolved, but changes in land-use (grazing and burning) and in climate (Little Ice Age) may have been important (Stevenson *et al*., 1990). The timing of the onset of peat erosion eliminates the possibility that recent acid deposition and atmospheric pollution initiated erosion at this site.

The western isles of Scotland

3.36 The western isles are largely treeless and there are widespread blanket bogs, largely due to the extreme oceanic climate. The blanket bogs on the Isle of Lewis are thought to be the most extreme 'Atlantic' blanket peat in the UK due to the north-westerly and island location (JNCC, 2008) with accumulations up 3 m deep. Birks & Madsen (1979) suggested that the Isle of Lewis has been largely treeless throughout the Holocene but there may have been local stands of *Betula* (birch) (Bohnke, 1988). However, Wilkins (1984) noted abundant macrofossil remains of trees, including *Pinus sylvestris* within the blanket peat of Lewis and Harris indicating changing environmental conditions in the past.

Forest of Bowland, Lancashire, England

3.37 Mackay & Tallis (1996) investigated erosion of a blanket mire complex at the Forest of Bowland. They suggested that the macrofossil evidence showed that *Sphagnum* dominated the vegetation for nearly all of the past 2000 years, but over the last 100 years it had disappeared from many areas. They concluded this was caused by summit-type erosion initiated by a combination of unusual factors:

1) low rainfall in the 1900s
2) decline in management standards during the 1st World War
3) lowering of the water table during an exceptional drought in 1921

3.38 These factors led to a catastrophic burn, probably in 1921, causing the removal of surface vegetation and the upper peat. This led to erosion and the demise of the bog. Atmospheric pollution was not directly responsible but may have influenced the *Sphagnum* present. They also concluded that sheep grazing at the Forest of Bowland might have prevented the recolonisation of bare peat surfaces, leading to further erosion of the bog.

North Yorkshire Moors, England

3.39 Simmons & Cundhill (1974) investigated 8 blanket bog sites in the North York Moors and undertook pollen and stratigraphical analyses. They concluded from the pollen evidence that in a limited area there was a marked variation in the pollen record and the peat accumulation rates, so even within a small area the factors controlling peat formation can be very variable. Because the dating used at this site was pollen stratigraphy, they could not date the timing of changes in peat accumulation rates. They identified evidence for anthropogenic influences throughout the period of blanket peat accumulation, but these were most strongly marked after the elm decline (6-5000 years ago). The pollen evidence indicates woodland clearance by humans at two sites, Howdale Hill and Yarsley Moss. No radiocarbon dates were taken, but using archaeological evidence, the woodland clearances were assigned to the Bronze Age and Medieval periods.

Keighley Moor Reservoir, West Yorkshire, England

3.40 Blundell & Holden (2015) recently investigated the peatland development history of this site from around 1500 years ago using stratigraphic techniques. They found that the current vegetation cover (dominated *by C. vulgaris*), has only been characteristic for the last c. 100 years. Before this time, *Sphagnum* mosses were much more prevalent, although their occurrence fluctuated with evidence of fire. After past fire events *Sphagnum* sp. routinely returned to the site. However, the most recent decline in *Sphagnum* appears to have been caused by a wildfire event, with subsequent burning for grouse moor management (to maintain heather dominance) preventing its return. They concluded that any attempts to raise the water table to encourage greater *Sphagnum* abundance would be appropriate given the past vegetation history of the site.

Which factors affect blanket bog erosion?

3.41 Peat bogs are important for carbon storage and this carbon will be released back into the atmosphere if the bog surface dries out and aerobic decomposition occurs. Many of the blanket bogs in the British Isles are currently being eroded, and this erosion is usually attributed to humans through moor burning, drainage, grazing with domestic animals, nitrogen deposition and/or direct removal by peat cutting for fuel. These human impacts are not always recent; blanket peat erosion was particularly severe in the Southern Pennines in the late 18th century (Tallis, 1995; Bragg & Tallis, 2001) and continues today. In many parts of this landscape the bogs have stopped growing and the peat has dried out and eroded, forming deep channels with peat islands (or haggs). The Southern Pennine blanket bogs are particularly vulnerable because of the relatively low rainfall (for blanket bog development) and the proximity of large human populations (Tallis, 1964, 1965).

3.42 However, peat erosion can occur naturally as a large body of peat can become unstable, leading to “bog bursts”. During exceptionally high rainfall, peat bogs can become saturated and collapse downslope, causing extensive erosion. Tallis (1985, 1987) suggested that Featherbed Moss in the Peak District became unstable after it had spread to the full extent of the topographic hollow where peat initiation began, which led to a build-up of unhumified peat at the surface. This led to a bog-slide (bog burst), where the top (vegetated) layer of peat slid downhill under the influence of gravity, leaving the remaining bare peat vulnerable to erosion.

3.43 Recent work suggests that some peat bogs are more robust than others and can endure a decrease in precipitation. Swindles *et al*., (2012) used a combination of high-temporal resolution proxy evidence from a small upland raised bog in North Yorkshire and compared it with a climate model to examine the relationship between rapid hydrological fluctuations in peatlands and climatic forcing. They demonstrated that changes in the water-table can occur independently of climate forcing and that a degree of internal stability partially disconnects peatland water-table behaviour from external climate forcing. Therefore, they suggest that some peatlands may also switch into reverse and start to accumulate peat again. They also highlighted that former erosion surfaces on blanket peats in Upper Conwy, North Wales have been found to be naturally regenerating. Further investigation is required to understand why some bog switch between erosion and accumulation and why some blanket bogs are more robust than others.

3.44 Afforestation via the establishment of forestry plantations can severely affect a blanket peat. Firstly, the ground is usually drained as the trees cannot grow in waterlogged conditions (Thompson *et al*., 2004). Secondly, trees growing on a mire surface take away water from the bog through evapotranspiration and growth, causing further drying. A high water table is required to maintain bog growth as it reduces oxygen diffusion from the surface and produces an anoxic layer in which peat is formed (due to inactivity of decomposers breaking down vegetation such as *Sphagnum*). Tree roots also take oxygen down further into the peat layer, resulting in aerobic decomposition at greater depth than would occur without trees.

3.45 Despite these negative effects of afforestation, some bogs have been shown to recover function. A good example of restoration of a bog is the border mires, in the uplands of west Northumberland and Cumbria. The border mires include raised bogs and blanket bogs with intermediate transition types in between. Between 1945 and 1960, trees were planted over much of the border mires where the peat was sufficiently "dry" and in other areas it was drained specifically to allow plantations to be established. Only the very wettest parts of the mires were left unplanted. A restoration project demonstrated that it is possible to restore a blanket bog by tree felling and damming of the drainage ditches. *Sphagnum* has been found to grow rapidly over deforested areas, even over chipped wood and tree trunks. It was concluded that the time taken for mires to return to their near original vegetation composition may not be as long as previously thought (Thompson *et al*., 2004).

3.46 The erosion of upland blanket bogs leads to the formation of gulleys, causing drainage and the lowering of the water-table in the surrounding peat. Natural erosional forces are frost, wind, rainfall and runoff. Therefore human induced initiation of peat erosion can be exacerbated by the local climate conditions. The surface vegetation of a peat bog protects the underlying peat and if the vegetation is removed the peat is vulnerable to erosion. Stevenson *et al*., (1992) investigated the evidence of peat erosion found in lake sediments in western Scotland (via an increase in organic content) and concluded that the colder, wetter and stormier climate during the Little Ice Age caused the initiation of peat erosion in the surrounding landscape. Changes in land use (grazing and burning) may also have been important (Stevenson *et al*., 1990) but the timing of the onset of erosion does not fit with the idea that recent acid deposition and atmospheric pollution was responsible for the initiation of erosion.

3.47 Bradshaw & McGee (1988) investigated lake sediment sequences from Wicklow and in Donegal, Ireland. They identified episodes of increased organic content of the sediment, which they used to determine the onset of erosion within the catchment. This showed an increase in erosion dated to 3000 years BP (radiocarbon years) in Wicklow and 1500 years

BP in Donegal. They therefore concluded that natural processes were responsible for the initiation of erosion rather than anthropogenic causes and that recent human activity has merely intensified erosion.

What is the efficacy of management/restoration on blanket bogs?

3.48 Before discussing the management of blanket bogs, it is worth revisiting what JNCC (2009) consider to represent blanket bog in good condition. Their criteria include:

- no loss of extent of blanket bog habitat;
- at least 6 indicator species present in a 4 m^2 quadrant;
- 50% of the cover should consist of 3 indicator species;
- *Sphagnum* cover should not just be *S. fallax;*
- Eriophorum vaginatum, Ericaceous spp, or Trichophorum cespitosum should not exceed 75% cover individually;
- low cover of non-native species, trees and scrub (except dwarf species) and mesotrophic grasses/forbs/bracken;
- low grazing/browsing on dwarf shrubs, especially young ones;
- no burning into moss/lichen layers, or to expose the peat surface, and no burning on sensitive areas assessed in the wider area;
- less actively eroding peat than re-deposited peat (in the wider area);
- less than 10% disturbed bare ground or showing signs of drainage or track damage; and
- less than 10% of *Sphagnum* should be damaged (crushed, disturbed).

3.49 In the light of the palaeoecological studies reviewed here, these appear to be sensible criteria in the main. However, the palaeoecological literature highlights the importance of hydrology in driving vegetation cover and indeed peat initiation and growth. We therefore suggest that a criterion on hydrological function would be a useful addition. Whilst the criteria for plant cover could be useful, and the focus here on maintaining a diversity of species reflects the natural variability in bog surface structure highlighted in the palaeoecological literature, the vegetation history of peat forming species is likely to be very site specific. Therefore, rather than setting an overall target for vegetation cover at all blanket bog sites, targets could instead be set by examining the palaeoecological evidence of vegetation history at each site (e.g. Blundell & Holden 2015) to determine the past condition of the bog.

3.50 Shepherd *et al*., (2013) reviewed the management of degraded blanket bogs, so what follows here is a summary of that publication, with discussion, where relevant, of the role the palaeoecological literature could play in informing restoration management. Broadly speaking, management might be carried out with the aim of:

a) Reversing drainage and so restoring hydrological function.
b) Stabilising bare peat and so reducing erosion of particulate matter.
c) Removing inappropriate vegetation.

Reversing drainage

3.51 This is usually achieved by blocking grips (drainage channels) in order to stop water from flowing through them and trap peat sediments. This can be achieved either by using dams made of plastic pilings, stone or wood, or bales of peat or heather. This results in a raising of the water table, particularly close to the dam. This appears in some cases to lead to an increase in wetland plant abundance, particularly of *Eriophorum angustifolium*, and an increase in the abundance of invertebrates, particularly crane flies. However, water tables are not raised to the level of intact bogs, at least in the short term. In addition, the balance of emissions changes, with reductions in CO_2 but increases in methane. The emissions of both of these gases are higher at sites with heather brash infill compared to open water sites or *Sphagnum* mats, although there do not appear to be any studies which compare the emissions levels of different types of dams. Shepherd *et al*., (2013) found some evidence that encouraging *Sphagnum* re-vegetation rather than *Calluna* or *Eriophorum* on the rewetted moor might reduce these emissions, but this has yet to be shown in the field. They also found that grips on shallower slopes may re-vegetate naturally and infill without being blocked, although they may still have a drainage impact. Because of the multiple benefits delivered (reduced erosion, restoration of hydrological function, re-vegetation and increases in invertebrate abundance), they concluded that blocking grips on steeper ground could be an effective solution for restoring blanket bogs. However, the optimal blocking material and the effect of subsequent vegetation management on emissions is unknown and should be investigated in order to minimize the negative effects of blocking grips on levels of greenhouse gas emissions.

3.52 In light of the palaeoecological literature reviewed above, restoring hydrological function to bogs appears to deliver multiple benefits. A high water table is needed for active peat formation, leading to growth and spread of blanket bog habitat. In addition, it may lead to recovery of *Sphagnum* mosses and help prevent invasion by trees. However, evidence from changes in humification rates indicates that most bogs have undergone natural cycles, with wetter and drier phases. Palaeoecological evidence could therefore be used to determine whether the current water table at potential restoration sites falls within the ranges that have supported blanket bogs in the past.

Stabilising bare peat/vegetation by appropriate peat-forming plants

3.53 This can be achieved by covering peat dunes with geojute or heather brash, by encouraging establishment of nurse grasses or by re-vegetating directly with *Sphagnum, Eriophorum* or *Calluna*. Shepherd *et al*., (2013) found no studies that quantify the effectiveness of dune stabilisation with heather brash or geojute in isolation, although some evidence was presented to support the role of geojute in aiding nurse plant establishment. Re-vegetation is more effective using upland natives rather than lowland grasses, since lowland grasses are less likely to establish. There is some evidence that adding both lime and fertiliser enhances establishment, but it is not clear if this tactic is equally effective for all species, or cost-effective. *Sphagnum* reintroduction is more successful where the water table is raised (so grip blocking might be expected to contribute to this, although regular flooding may be detrimental). In addition, high humidity alongside shade fabric, nurse vegetation or mulch can be helpful, such that dune stabilisation might also help create the correct conditions for *Sphagnum* reintroduction. Lastly, the location of collection of *Sphagnum* diasporas also matters: the top 10 cm of intact bog apparently produces the best propagules, but this depends on the species used and the physico-chemical conditions of the peat substrate. *Sphagnum* has begun to regenerate naturally in some places.

3.54 The palaeoecological literature could be used here to inform the choice of species for re-vegetation. For example, since *Calluna* is associated with drier bog surface wetness, there are likely to be some areas where it will establish readily, and other, wetter areas where other vegetation such as *Sphagnum* would be more appropriate. Even within wet areas, the optimum species of *Sphagnum* chosen might vary depending on whether a pool is present or not. Finally, because nutrient input is implicated in the decline of some species of *Sphagnum*, the addition of lime and fertiliser might not be appropriate in areas where the main aim is eventual recolonisation by *Sphagnum*. In areas where this form of restoration has taken place, palaeoecological studies might inform which species might be able to establish in more fertile conditions. Although *Calluna* is associated with drier bogs, it is not known whether its presence causes drying of the surface, and research to inform this would help determine whether *Calluna* establishment is a suitable management action if the aim of restoration is to raise the water table.

Removal of inappropriate vegetation

3.55 Shepherd *et al*., (2013) found evidence in the literature for success in bog recovery after deforestation, particularly where plantations are less established and on flatter sites. Indeed, they highlighted that tree removal with no further management may be enough to start the process of change towards a more typical blanket bog vegetation community. This tentative conclusion is supported by the work of Moore (1973, 1975), who suggested, based on the timing of peat initiation, that tree removal was implicated in blanket bog formation in the first place in many areas. In addition, Smith and Cloutman (1988) found charcoal in the basal layer of peat at a site in South Wales, suggesting a role for the human clearance of forest in peat initiation. However, other palaeoecological evidence (Tallis, 1975) shows the presence of trees long after the initiation of peat formation in the Pennines, so in some cases deforestation may not be necessary. Based on the existing literature, it remains unclear why in some areas deforestation might immediately precede peat formation whilst in others peat formation began before the forest was cleared.

3.56 In addition, Shepherd *et al*., (2013) found literature to suggest that the dominance of *Molinia caerulea* can be reduced by vigorous cutting, grazing and herbicide treatments. However, they found no literature on the removal of *Calluna vulgaris* or other plants that might out-compete *Sphagnum*. Shepherd *et al*., (2013) highlighted that it is worth considering whether control of these wetland plants is cost effective given that these plants are likely to be part of the ongoing cycle of vegetation change, over millennia, in blanket bogs. They support valuable functions such as peat formation and regulating water quality, even if they don't represent an unmodified blanket bog community.

3.57 The palaeoecological evidence reviewed here confirms that the surface vegetation found on blanket bogs varies over time and with changes in hydrological conditions. *Calluna* is found on drier bogs with higher levels of humification. It is possible that its roots may act like those of trees and allow oxygen to penetrate to lower levels, speeding the humification process and drying out the peat further. Indeed, management for a relative monoculture of *Calluna* may prevent recovery by other species typical of wetter bogs. Experiments to determine whether *Calluna* grows in places that are already dry or acts to dry out the peat (or both) would be a useful addition to inform management in this respect.

Conclusions

What are the climatic conditions required for peat formation?

3.58 Peat forms in cool, wet areas with high rainfall and few dry days. Different factors appear to have been important in different places and at different times in initiating peat formation. Because peat initiation began at different times even within quite small areas, it seems likely that topography (which varies more than climate over small spatial scales) plays an important part in modifying conditions and allowing peat to form. Human activities such as grazing and forest clearance have also been implicated in peat initiation, but not at all sites. Peat cores can be used to reconstruct past climatic conditions, and these reconstructions could be used in conjunction with climate projections to determine whether the conditions at a site are likely to remain within the range of conditions that supported peat formation in the past. However, using palaeoecological data to model responses of peat to past climate change would not be appropriate, because climatic conditions are often inferred based on the bog surface wetness as calculated by the relative humification of layers of peat – this would result in circular reasoning.

Which species are involved in peat formation? Are these consistent across space and time?

3.59 The surface vegetation found on individual blanket bog sites has changed over time, often (but not always) associated with changes in hydrological conditions. Across the UK, some species of *Sphagnum* were more common on blanket bogs in the past than they are now. Even within the group of plant species preferring wetter conditions, different species are found within different locations on the bog. At some sites, the vegetation that is currently present is very different to that which occurred over the majority of that site's history. This means that having a universal set of criteria for the outcomes of management and/or restoration might not achieve the best outcome for a particular site in terms of restoring the site to its historical condition or for creating a robust bog that is able to withstand changes in climatic conditions. Instead, targets could be developed for individual sites, taking into account the past vegetation history and likely future climate trajectory.

Which locations have a long history of peat formation?

3.60 A number of sites have been accumulating peat for thousands of years, located in areas with suitable climatic conditions. A number of these have records of forest and other vegetation present at different times in the history of the bog. This highlights that some bogs are relatively robust and have persisted in the same location over time despite periods of less suitable climatic conditions. More studies on the factors that allow bogs to recover following these periods of unsuitable climate would be useful in informing management in the future.

Which factors affect blanket bog erosion?

3.61 Several factors have been implicated in blanket bog erosion, and these differ on a site by site basis. They include changes in climatic conditions, afforestation (resulting in a drier bog surface), burning, grazing, and management. However, the timing of the onset of erosion at some sites rules out atmospheric pollution and acid deposition as a factor. Some sites appear to be more robust than others, and some have switched naturally between erosion and accumulation over time, but the factors controlling these variations are not known.

What is the impact of management/restoration on blanket bogs?

3.62 Management generally aims to restore hydrological function, stabilise bare peat and/or remove inappropriate vegetation. The palaeoecological evidence supports the reasoning for the first of these, since peat initiation and growth is associated with wetter periods. In terms of stabilising bare peat, the past vegetation record of a site could be used to help choose suitable plants to achieve stabilisation and to project which are likely to be able to remain at a site in the future given projected climatic changes. In the past, deforestation has been associated with peat initiation at some sites, so forest removal might be expected to restore blanket bog function. In some places deforestation might not be necessary to achieve blanket bog recovery, although it is not known why. *Molinia* is also often targeted for removal, but the historical record shows that it can form peat in isolation (Shepherd *et al*., 2013) and so might be a valuable component of blanket bog systems. However, because *Calluna* is associated with drier peat (which is more likely to erode), it might be necessary to consider removing it from some areas, along with careful monitoring to determine whether this relationship is causal.

4 Knowledge gaps and recommendations for future research

4.1 Several knowledge gaps have been highlighted in the preparation of this report. To begin with, not all bogs across the UK have had peat cores taken, so the geographical coverage of palaeoecological surveys of past vegetation history and bog surface wetness is not complete. In addition, within each site the number of sections taken tends to be low, reflecting the effort that is put in to achieving a high temporal resolution across a long time series. This limits the generalities that can be drawn from such studies, especially given that peat initiation appears to be very site specific and can vary considerably over very small spatial extents. A more recent study (Blundell & Holden 2015) took a large number of cores to give a very good spatial coverage of the study site (stratigraphy was recorded for 88 cores across a 1.48 km^2 site). However, these cores had a much lower temporal resolution (split into 5 sections across the entire peat depth) and only a master core was examined at high temporal resolution due to the amount of work this entails.

4.2 In addition to the limitations caused by the trade-off between spatial and temporal resolution, there are several interesting possibilities that have not yet been fully investigated. For example, there is evidence that some bogs have switched between erosion and accumulation in the past, but the cause of this switch is not known. Some bogs also appear to have been more robust than others, but why this might be is also unknown. More studies on the factors that allow bogs to recover following periods of unsuitable climate would be useful in informing management in the future. Finally, there is plenty of evidence for natural cycles of wetter and drier periods within individual bogs. However, there is yet to be a study (even a meta-analysis) that determines the main driving factor – for example if all bogs were either wetter or drier at the same time, then climate might be the main factor driving these changes, which would have implications for management under continued climate change. One option for management would be to simply allow these natural cycles to occur, but it is not known how much blanket bog might be considered adequate to allow maintenance of bogs in different stages of the cycle, or whether these cycles might continue in non-analagous climates.

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Appendix 1 - Literature search reference list (Full)

Appendix 1 - Literature search reference list (Full) is available in the form of an excel spreadsheet and supplement this report.

Appendix 2 - References included in the review report

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