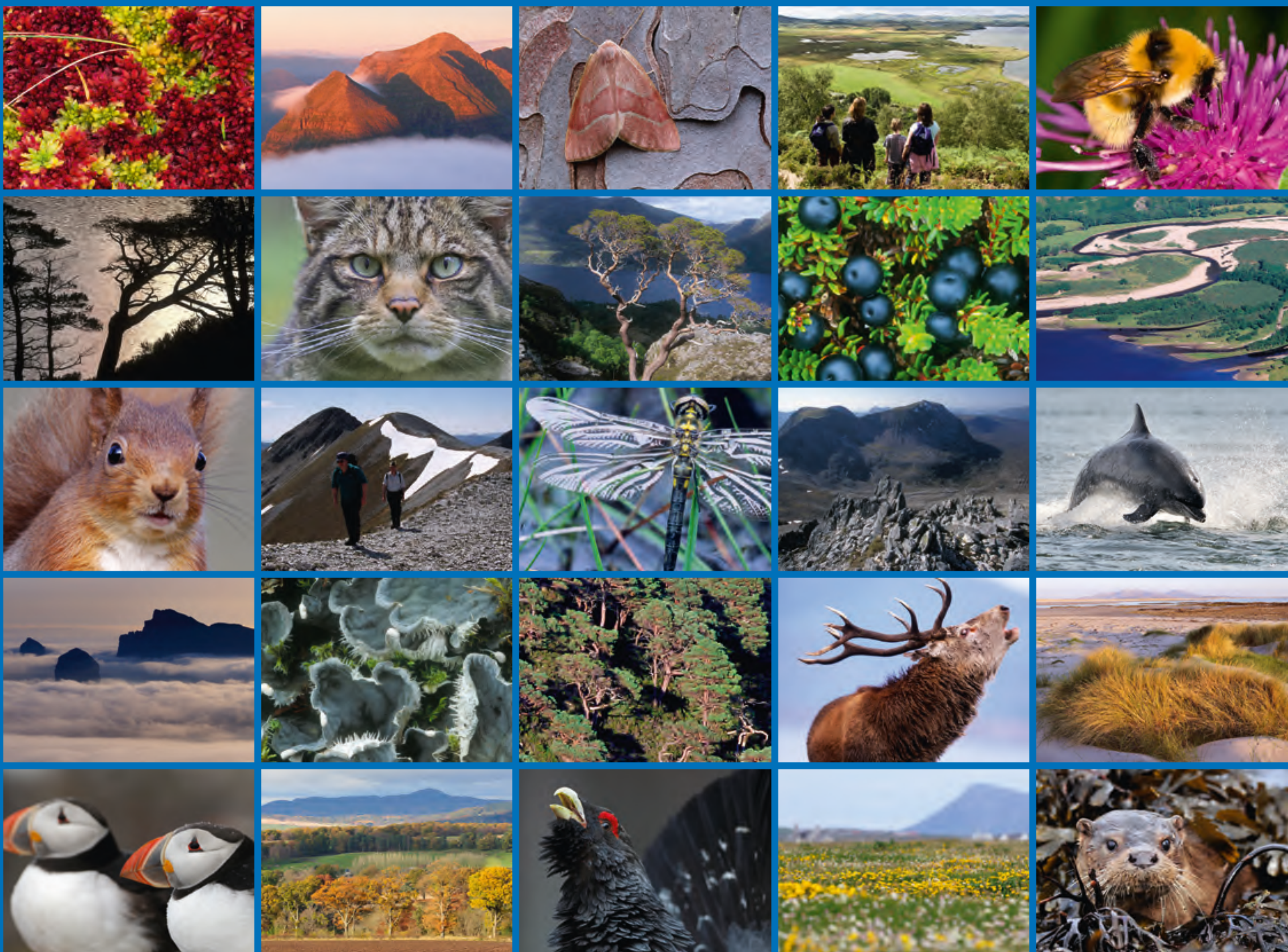
Scottish Natural Heritage
Commissioned Report No. 925

A review of the influence of ombrotrophic peat depth on the successful restoration of bog habitat



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COMMISSIONED REPORT

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This report should be quoted as:

Lindsay, R.A. & Clough, J. 2016. A review of the influence of ombrotrophic peat depth on the successful restoration of bog habitat. *Scottish Natural Heritage Commissioned Report No. 925.*

COMMISSIONED REPORT
Summary

A review of the influence of ombrotrophic peat depth on the successful restoration of bog habitat

Commissioned Report No. 925
Project No: 15222
Contractor: Richard Lindsay and Jack Clough, University of East London
Year of publication: 2016

Keywords

Peat; depth; extraction; consent; minimum; residual; bog; ombrotrophic; restoration.

Background

A number of raised bogs in Scotland currently have planning consent for commercial peat extraction. All of these consents are now subject to periodic review through the Renewal of Mineral Permissions ("ROMP") process. Whereas in earlier times such consents imposed relatively few conditions in relation to after-use, expectations are now increasingly focused on restoration of the original raised bog habitat and conditions are thus being imposed accordingly, both on consents subject to ROMP and also on any new consents which may be granted.

Bog peat is formed when the living, peat-forming surface is no longer able to draw on the underlying mineral sub-soil, or on the mineral-enriched groundwater table, and is thus wholly dependent upon direct precipitation inputs for its supply of water and solutes – in technical terms it becomes 'ombrotrophic'. If a peatland site is to be restored to ombrotrophic bog following commercial peat extraction, a residual layer of peat must remain in order to form a barrier between the mineral-enriched conditions of the sub-soil with its associated water table, and the peat-forming vegetation newly-established on the bare peat surface after extraction ceases. In some cases the condition imposed in relation to this residual peat layer has been to require retention of 'an average minimum peat depth of 0.5 m'. Both the origins and likely efficacy of this condition do not appear to have been subject to scrutiny at any point. This report seeks to assess the concept of 'an average minimum peat depth of 0.5 m' as a requirement for restoration of ombrotrophic bog vegetation on commercially cut-over bog systems, based on available published material.

Main findings

- There appears to be no published scientific literature, nor any official guidance, which recommends use of an 'average minimum residual peat depth of 0.5 m' for restoration of bog habitat;
- Typically, lowland raised bogs tend to have basal layers of fen peat which are, on average, a little under 2 m deep and thus if the residual peat thickness is less than 2 m there is a strong possibility that any restoration efforts will necessarily begin on a mineral-enriched fen-peat layer;

- The vast majority of literature concerned with residual peat depths for *peatland* (not necessarily *bog*) restoration has in the past emphasised the need for a minimum residual peat thickness of 0.5 m provided the peat is strongly humified (at least H7 on the von Post scale);
- There has also been consensus in the past that neither the extraction process itself, nor the drainage system, should cut into the mineral sub-soil;
- If the peat is not so strongly humified, it has been recommended in the past that the residual peat layer should be at least 1 m deep;
- Evidence from sub-peat layers of raised bogs in the UK indicates that many sites have somewhat variable sub-peat deposits and thus it is not reasonable to proceed on the basis that a peat bog is underlain by impermeable deposits unless a detailed survey of sub-peat deposits has been undertaken;
- Strongly humified peat shrinks and cracks more readily than less humified peat and thus even where a minimum layer of 0.5 m of strongly humified has been recommended in the past, it has also been recommended that this peat layer should be covered with at least a 20-30 cm layer of 'top-spit' material to minimise the possibility of drying out and cracking;
- Shrinkage due to drying during the last stages of peat extraction and prior to the water table being raised across the site as part of the restoration programme will mean that a residual peat depth of 0.5 m at cessation of extraction will be less than this by the time the restoration programme is established;
- Although a great many restoration schemes have been undertaken in the UK, Northern Germany and Canada, *none* of these has yet established an ombrotrophic bog vegetation, the dominant vegetation generally being a 'poor-fen' type which is a pre-cursor for establishment of bog vegetation;
- All these restoration programmes have been undertaken on areas where the residual peat thickness has generally been somewhat less than 2 m deep and thus are likely to be influenced to greater or lesser degrees by proximity to, or establishment in, fen peat deposits, enhanced still further by any water which irrigates the surface vegetation having been in contact with the mineral sub-soil through cracks in the peat;
- Under natural conditions, such poor-fen vegetation can persist for 200-300 years, suggesting that the restoration programmes which are currently dominated by poor-fen vegetation may remain in this state for a considerable period into the future;
- A major review of spontaneous re-vegetation recovery on milled peat sites in Estonia indicates that a minimum residual peat thickness of 2.3 m is required if ombrotrophic bog vegetation is to establish successfully without a poor-fen phase;
- Experimental work based on the Estonian recommendation of 2.3 m for the residual peat depth indicates that on a former milled site with a residual peat depth of 2.5 m it is possible to re-establish ombrotrophic bog habitat directly.

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Acknowledgements

The authors would like to acknowledge the funding, support and assistance provided by Scottish Natural Heritage in support of this work, particularly Malcolm Fraser, Deborah Spray and Andrew McBride. Their assistance and comments were greatly appreciated. We would also like to express our thanks to the Library Service of the University of East London, who assisted in obtaining the majority of our reviewed journal papers and helped in tracking down some of the more obscure items.

1. INTRODUCTION

Scottish Natural Heritage has commissioned the University of East London to carry out a literature review of research relevant to the minimum depth (and type) of peat required for successful restoration to bog habitat. The review is required to include an assessment of the likely effects of the application of an average minimum depth rather than a minimum depth on the success of bog restoration plans - both in relation to the likelihood of successful establishment of bog vegetation and on the timescales for restoration.

1.1 Background

1.1.1 Planning context

In the immediate post-war period, as part of the drive to stimulate economic re-development of Britain after the years of conflict, a number of consents for commercial peat extraction were issued in the form of Interim Development Orders (IDOs). These consents contained few conditions in relation to restoration and after-use, partly to avoid placing what might be perceived as undue constraints on developers, partly because the overall number and intensity of such operations across Britain were regarded as relatively low, and partly because there was little general concern about peatland habitats at the time. The situation changed in the 1960s when much of the horticultural industry and horticultural market moved from use of loam-based composts to the use of peat as the favoured growing medium. Planning consents were issued for the opening up of new commercial peat-extraction operations on a number of peatland sites but the conditions relating to after-use were still limited and rarely, if ever, addressed the possibility of returning the site to some form of peatland habitat at the end of commercial operations.

In the 1980s a second major change took place within the peat industry. Up to this point, commercial extraction had used a technique which created alternating raised baulks (on which the cut peat was stacked in 'sods' to dry) and wide trenches created as the peat was cut from the bog. The depth of cut meant that the processable volume of annual crop was often obtained from only a portion of the whole site, meaning that certain parts tended to lie unworked for anything from one to several years. This often gave rise to a 'mobile mosaic' of naturally regenerating peatland vegetation, at least in the rows of wet trenches. In the 1980s, however, the technique of peat 'milling' began to be adopted by an increasing number of peat companies. This process involved creating a flat, bare peat surface across the whole area of a peatland site, from which a thin skim of peat was then taken in a series of passes during the extraction season.

This intensification of extraction method and consequent loss of the remnant biodiversity 'mobile mosaic', combined with increasing concern about the pressures coming to bear on the UK's peatland habitats (Lindsay *et al.,* 1988; Lindsay, 1993) which were becoming increasingly valued for their distinctive biodiversity, led to a change in approach to the after-use of peat extraction sites. Indeed difficulties arising from a number of post-war IDOs issued for a range of mineral extraction operations had already placed a legal obligation on planning authorities, through the Town and Country Planning (Minerals) Act 1981, to review *all* planning consents for mineral extraction and, if appropriate, amend these consents to reflect current priorities of society. This system was subsequently clarified and strengthened through the Environment Act 1995 for England and Wales, while the Town and Country (Scotland) Planning Act 1997 provided planning authorities in Scotland with the means to review and amend existing planning consents.

Around the same time, a Peat Working Group (PWG) was convened in 1992 by the Department of the Environment in response to widely expressed concerns about the diminished extent and poor condition of peatland habitats, at least in the lowlands of Britain, and the fact that commercial peat extraction was now perceived as one of the most active threats to the remaining examples of such areas. The PWG was tasked with reviewing, across Britain as a whole, the current position and potential future balance between the needs of nature conservation and those of the commercial peat extraction industry. The conclusions and recommendations of the PWG which have direct relevance to the present review were that commercial peat extraction should continue but would involve no more than an anticipated maximum of 1,000 ha of new worked areas, and in the expectation that planning consents would be updated for all worked areas particularly to encourage and guide restoration of peatland habitat as the anticipated after-use (Department of the Environment, 1994). In order to give impetus to these recommendations, the Department of Environment also commissioned a review of available evidence relating to the restoration of damaged peatlands, particularly those which had been subject to commercial peat extraction (Wheeler and Shaw, 1995). It was intended that the review would provide guidance to the industry, site managers, environmental bodies and planning authorities about the conditions necessary for, and the techniques available to best achieve, peatland restoration.

At the time of the WPG Report, 29 production sites (with 38 planning permissions – other than the Somerset Levels which had many small consents) were identified for England and Wales and 69 production sites in Scotland. As a result of these various initiatives, planning authorities increasingly began to consider and review the conditions linked to existing planning consents for commercial peat extraction as well as apply these new principles of peatland restoration to new applications.

The current position is that planning consents for peat extraction are now subject to separate regulatory procedures in England and Scotland (Wales currently has no commercial peat extraction sites) through the Review of minerals planning conditions in England and the 'ROMP' (Review of Mineral Planning Permissions) process in Scotland. In 2008, England had 10 active consents while Scotland had 57 possible active consents, the uncertainty for Scottish sites arising because the status of several consents was unknown (Roger Meade Associates/Maslen Environmental 2008).

Based on the body of information available through the initiatives described above, planning authorities have begun requiring that a plan for restoration to peatland at the end of working be drawn up as a condition of consent, and have also tended to impose a limit on the depth to which extraction will be permitted in order to provide a favourable starting-point for such after-use restoration.

This last condition – retention of a thickness of peat at cessation of the consent period – forms the core of the present review because the 'depth of remaining peat' is becoming an increasingly contentious issue. The thinner the layer required to be left, the more peat the company can extract and sell before reaching the limit of its consent conditions. Balanced against these commercial concerns are equally valid concerns that the thinner the layer of peat which remains, the more difficult it will be to achieve the required form of peatland restoration. The reasons why this is so are considered in the next section.

1.1.2 The ecological basis of a 'minimum peat depth'

Current consents for commercial peat extraction in some cases impose no requirement for any peat to be retained at the end of the consent period, but in many there is a requirement that an 'average minimum peat depth of 0.5 m is retained', in other cases a 'minimum peat depth of 0.5 m' is required, while still others require a 'minimum depth of 0.5 m of ombrotrophic bog peat' is retained. This last variant – a minimum depth of 0.5 m of ombrotrophic bog peat – highlights a number of key issues about this particular planning condition.

1.1.2.1 Peat, peatland and peat bog

'Peat' consists of the dead remains of plant materials, laid down *in-situ*, which have failed to decompose entirely because they are waterlogged. Peat can be generated by a large variety of plant materials – even trees, in the tropics – as long as the materials are kept sufficiently waterlogged. Peat can form extensive tracts of organic soil and can accumulate great thicknesses. Wherever a peat soil has formed, the land is classed as a 'peatland', whatever the nature of the plant materials forming it and the present nature of the vegetation cover. Peatlands therefore display a huge variety of forms, not only globally but also within the UK. Consequently if a planning condition states that a site should be 'restored to peatland' at the end of the consent period, a great many possibilities exist for the restoration programme.

The vast majority of commercial peat extraction in the UK is, however, undertaken on lowland peatland sites, unlike in the Republic of Ireland where extensive areas of 'upland' peatland are subject to industrial extraction (but this is mainly for use in electricity generating stations rather than for the horticultural market). Commercial peat extraction in the UK is now almost entirely restricted to one type of lowland peatland, although in Medieval times industrial-scale extraction is now recognised to have been extensive throughout a range of peatland types in both the uplands and lowlands. The material which is today most favoured for professional horticulture is peat with a high content of little-decomposed *Sphagnum* bog moss.

While differing species of *Sphagnum* bog moss can be found growing in a variety of environmental conditions and peatland types, the least decomposed *Sphagnum* is most reliably found in lowland sites where the dead, partially-decomposed remains of *Sphagnum* accumulate as a large raised mound of peat. This mound is maintained in a waterlogged state purely by direct precipitation because accumulation has raised the mound above the influence of the local groundwater table. The fact that this mound of *Sphagnum* peat is maintained in its waterlogged condition solely by direct precipitation means that the site is categorised as 'peat bog'. More technically, the fact that it receives its water – and also therefore its nutrients – only through direct precipitation means that the site is termed 'ombrotrophic' ['fed by rain showers']. This contrasts with peatlands which are waterlogged by groundwater or surface-water accumulation and are thus enriched by whatever nutrients are brought into the system from the catchment. Such peatlands are technically known as 'minerotrophic' peatlands, and are more commonly known as 'fens'.

The accumulated *Sphagnum* fragments often do not decompose to any significant degree under such conditions. This is, firstly, because they are maintained in a constantly waterlogged state by regular inputs of precipitation. Secondly, *Sphagnum* itself is well adapted to retain whatever precipitation lands on the dome surface and thus maintain constantly-waterlogged conditions. Thirdly, nutrient levels in the rain supply are so low that the *Sphagnum* plant itself contains only limited nutrition for decomposer organisms and they themselves can find few nutrients to draw on. Finally, *Sphagnum* goes some way to immobilising decomposer microbes by releasing into the surrounding waterlogged matrix a pectin-like chemical called sphagnan which inhibits microbial functioning.

For fairly obvious reasons these domes of peat, sitting within the landscape as raised mounds, in some cases covering several square kilometres, are termed 'raised bogs'. They typically accumulate a thickness of peat which may exceed 10 m and the peat is generally fairly rich in the remains of *Sphagnum*, thus making raised bogs particularly attractive to the horticultural industry. In addition, being mostly located in the lowlands and thus not subject to the high levels of precipitation and cloud cover which characterise upland areas, lowland raised bogs experience a climate which is far more conducive to the drying of a commercial peat crop than the extensive peatlands which dominate much of the uplands.

1.1.2.2 Restoration targets – 'peatlands' or 'peat bog'?

When it comes to setting restoration targets as a condition of planning consent for a commercial peat extraction site, various options are available:

- 'Restoration to agriculture' was often a favoured option in the past, although this took no account of the fact that the site had originally been a wetland and did not represent any form of restoration as now understood by the term;
- 'Restoration to wetland' has been an after-use target widely employed in the Republic of Ireland, with extensive lakes and reed-beds established on the sites of former extraction sites, thereby replacing the original peat-forming system with various types of water body;
- 'Restoration to peatland' seeks to re-establish a system capable of peat formation, although it does not specify what sort of peatland should be created, thus providing the possibility of replacing a peat bog system with a fen peatland – a very different habitat from the one which is likely to have existed prior to commercial peat extraction;
- 'Restoration to [ombrotrophic] peat bog habitat' provides the closest 'like for like' option, given that the majority of sites subject to commercial peat extraction are ombrotrophic raised bogs, whereas the previous options more accurately represent 'conversion to a different habitat' – at least on the timescales normally associated with planning consents.

If the last option – restoration to peat bog habitat – is specified as a planning condition, the remaining depth of peat left in the ground, and the nature of that peat, may be important factors in determining whether this condition can be met. The next section explores why this may be the case.

1.1.2.3 Formation and development of an ombrotrophic raised bog

Formation of a lowland raised bog typically begins with a shallow lake which is gradually colonised by fen vegetation and the lake subsequently becomes infilled with fen peat. Water seeping from the surrounding catchment into the centre of the former lake is stripped of its nutrients by the marginal zones of vegetation, resulting in central parts becoming increasingly nutrient-poor and somewhat acidic, while still being completely waterlogged. These are conditions under which certain species of *Sphagnum* can thrive, particularly those associated with what is termed 'poor fen' habitat. *Sphagnum* grows as carpets or cushions in which a great many individual stems clump together, rather than growing as individual plants. These carpets begin to acidify the water even more, rendering conditions increasingly unfavourable for many plant species and thus enabling the *Sphagnum* to become established as a dominant component of the ground flora.

The combination of waterlogging, acidification and release of sphagnan into the surrounding waters causes decomposition of dead plant material to slow substantially. As the carpets and cushions of *Sphagnum* grow, they consequently accumulate increasing quantities of dead plant material and the living surface begins to rise above the surface of the infilled lake. In regions where the local climate is relatively humid and provides sufficiently regular precipitation inputs (and probably most, if not all, of lowland Britain qualifies in this respect), *Sphagnum* is able to retain these precipitation inputs within its various storage systems and maintain waterlogged conditions even in carpets, cushions or hummocks which have risen significantly above the groundwater table of the former lake. Once these *Sphagnum* surfaces have risen further than some 30 cm above the groundwater table, capillary action is no longer capable of supplying the living material with any groundwater nutrients and the living surface becomes entirely dependent on direct precipitation for all water and nutrient supplies – it has become ombrotrophic bog.

Over a period of time, these various elevated mounds coalesce into a single large mass which, because conditions are now so extremely acidic and rich in sphagnan, begins to accumulate bog peat at a steady rate of perhaps 1-2 mm per year. After 6-7 millennia, this dome may rise to a height of 10 m or more above the surrounding landscape and beneath this large thickness of bog peat the original fen peat lies as a layer compressed between the mass of bog peat above it and the mineral-soil base of the original lake. This process of peat bog formation by lake-infilling is termed 'terrestrialisation' (see Figure 1).

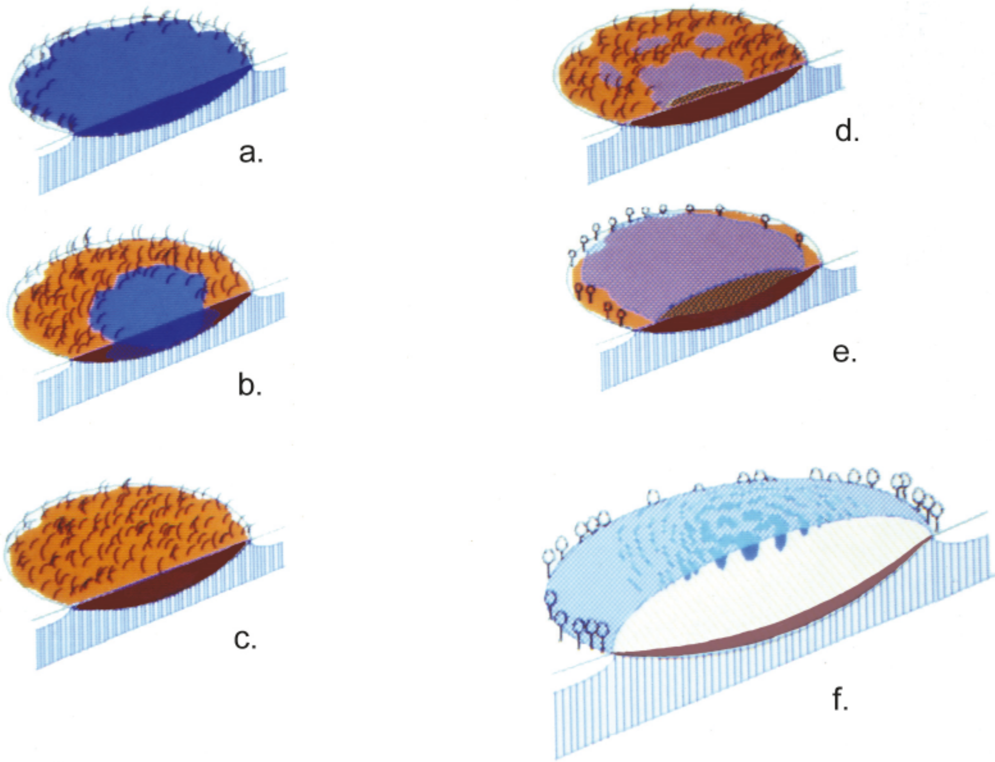


Figure 1. Raised bog formation through terrestrialisation. (a) An initial shallow lake. (b) Fen vegetation develops around the lake margin and begins to accumulate fen peat. (c) Fen peat now completely fills the original lake basin which is now completely covered with fen vegetation. (d) Towards the centre of the fen conditions are nutrient-poor so Sphagnum colonises to form carpets and hummocks which slowly rise above the influence of the groundwater table. (e) Sphagnum carpets and hummocks coalesce to form a single dome of ombrotrophic peat which expands steadily to cover almost the whole area of fen. (f) Eventually ombrotrophic bog peat accumulation may result in a dome which rises 10 m above the surrounding landscape and the original fen peat is compressed into a layer beneath the bog peat. The bog surface is typically dominated by a mosaic of hummocks and hollows, but if the climate is sufficiently wet the bog dome may support pools of open water. © Richard Lindsay

As the raised bog develops, however, runoff from the bog dome and impeded groundwater around the margin of the bog together result in waterlogging of surrounding mineral ground which was formerly dry. Such waterlogging enables the bog to grow out across this formerly-dry ground and thus expand beyond its original lake basin in a process termed 'paludification'. In this way a raised bog which formed originally as a relatively constrained dome through terrestrialisation may eventually spread to become an extremely large raised bog through paludification (Rydin and Jeglum, 2006, Fig. 7.4). An important point to note is that on ground which becomes part of the bog through paludification, the layer of fen peat lying between the mineral-soil base and the overlying thickness of bog peat may be relatively thin compared to the layer of fen peat associated with the original terrestrialised basin. To complicate things further, it is not unusual in the UK to find that two adjacent raised bogs have coalesced to form one larger raised bog through the process of paludification (see Wheeler and Shaw 1995, their Fig.1.1 B), thus creating a more complex pattern of thinner and thicker layers of fen peat beneath the layers of bog peat.

If peat extraction proceeds until the fen peat underlying the bog peat becomes exposed, any subsequent restoration programme would be commencing on a surface which reflected an earlier phase in the development of the bog and would not therefore provide starting conditions which are associated with ombrotrophic bog habitat. This therefore raises the question of whether a planning condition which requires that restoration should be to peat bog habitat can be met – or at least met in any meaningful timescale.

Currently, a frequently applied after-use condition is that the peat company should leave an 'average minimum residual peat depth of 0.5 m' in order to facilitate restoration. Increasingly, however, consents are specifying that restoration should be to peat bog habitat rather than to a more generic wetland or peatland habitat. While there is little doubt that if an average minimum peat depth of 0.5 m remains across the site then some form of fen peatland could be established, it is not clear that such a peat layer would assist in the restoration of peat bog habitat – indeed there is some concern that it may actually delay or prevent bog development.

The present review has therefore been undertaken in order to examine the existing evidence for and against the use of an 'average minimum residual peat depth of 0.5 m' as a planning condition, and to assess whether current evidence points to any particular residual depth of peat, of any particular type, which would permit continued peat extraction down to this agreed limit but which would also provide confidence that restoration to bog habitat would be achievable within a meaningful timescale.

1.2 Scope of the Review

Given that the majority of commercial peat extraction operations in the UK occur on lowland raised bogs and that this habitat is the focus of interest in terms of restoration, while the concerns about restoration include the possible influence of poor-fen conditions, the present review will confine consideration to two types of peatland ecosystem – lowland raised bog and poor-fen habitats. Though a small amount of commercial peat extraction occurs on blanket bogs in the UK and blanket bogs are ombrotrophic bog systems, the environmental and morphological characteristics of blanket bogs differ sufficiently from lowland raised bogs for a great many features of the blanket bog habitat to have little relevance to the current question. Consequently information associated with blanket bogs and blanket bog restoration will not be considered by this review. Neither will information about the richer fen systems of the UK because only a few examples of raised bog in the UK occur within limestone-dominated landscapes and none of these sites is, or is likely to be, subject to commercial peat extraction.

The review will draw on ecological processes which occur in relevant natural peatland systems where these may shed light on the restoration process. As the fundamental characteristics of raised bogs are remarkably similar throughout the Northern Hemisphere and at least parts of the Southern Hemisphere – even down to the presence of many of the same *Sphagnum* building blocks – information from studies undertaken outside the UK will be included where the habitats involved are considered to be sufficiently comparable to UK examples. This is particularly important as much research work on peatland restoration following commercial peat extraction has been undertaken on raised bogs in Canada.

The review seeks to provide information which can help to inform decision-making about appropriate planning conditions for operations proposed for, or already being undertaken on, lowland raised bogs, but the review will not make recommendations with regard to planning conditions or restoration management strategies.

1.3 Objective of the Review

1.3.1 Primary question

Is an average minimum residual peat depth of 0.5 m appropriate for the restoration of peat bog habitat following commercial peat extraction?

1.3.2 Sub-questions

The over-arching question can then be explored through the following sub-questions:

- What is the typical thickness of the fen-peat layer in a lowland raised bog?
- Does residual peat depth influence surface-water chemistry and bog restoration?
- Does residual peat depth influence the hydrology of bog restoration?
- Does residual peat depth influence the vegetation achieved during bog restoration?
- What is the timescale of transition from poor-fen conditions to ombrotrophic bog in natural or managed peatland succession?
- What are the potential effects on a bog restoration programme of using a residual peat depth having an average minimum depth of 0.5 m?

1.3.3 Key definitions

'Bog restoration' is taken to mean restoration of a vegetation dominated exclusively by species typically found in the 'terrestrial' parts of natural raised bog vegetation and not consisting largely of species found only in the hollows of a natural bog, nor containing species generally restricted to the fen margins of a raised bog or other minerotrophic fen habitats.

'Poor-fen' is taken to mean vegetation which is normally associated with solute-poor minerotrophic conditions, characterised by species typically associated with such conditions as may be found in the lagg fen margin or the flushed lower slopes of a raised bog margin but not normally occurring within the ombrotrophic bog vegetation of the bog dome itself.

'Commercial peat extraction' is assumed generally to be in the form of surface milling (or vacuum harvesting as it is sometimes referred to in Canada and Finland). 'Sod cutting' to create 'baulks and hollows' will also be considered inasmuch as it sheds light on the question of minimum residual peat depth, although the question of 'average minimum depth' is not so applicable to sod cutting methods because of the large height difference between the baulks and the hollows.

'Peatland' refers to any system with a peat deposit or having peat-forming capability and makes no distinction between bog peatlands and fen peatlands.

'Sphagnum' refers to any member of the genus *Sphagnum*, or bog moss. There are many species of *Sphagnum* in the UK, some being almost exclusively bog species, others being found in both bogs and fens, while others are found only in fen habitats. Mention of *Sphagnum* alone, without an indication of the species of *Sphagnum*, gives no indication of whether the habitat is bog or fen, although it is likely to be a peatland.

2. METHODS

The present review involves a systematic literature review of available information relevant to the issue of minimum residual peat depths and restoration to bog habitat following commercial peat extraction. The review aims to answer the primary question through consideration of the various sub-questions listed above, followed by a synthesis of the information from these sub-questions in order to address the primary question.

2.1 General principles

The 'PICO' (population, intervention, comparison, outcome) framework and similar approaches to systematic review provide a logical structure to the process of collating and assessing a set of studies because they bring clarity to the search strategy and evaluation process (Stone, 2013; Haddaway *et al.,* 2014). In the case of the present review, the components were identified as:

- Population: lowland raised bogs formed from *Sphagnum* rather than Southern Hemisphere cushion plants and Restionanceae wire grass, together with associated poor-fen systems, with particular reference to sites subject to commercial peat extraction;
- Intervention: either the natural successional process associated with development from minerotrophic fen conditions to ombrotrophic bog conditions, or restoration management of commercially-worked raised bog sites to re-create peatland habitat;
- Comparison: either comparison of restoration results against the process of natural succession, or comparison between restoration sites having differing depths of residual peat;
- Outcome: Restoration of ombrotrophic bog vegetation across former areas of commercial peat extraction on raised bog sites.

2.2 Evidence search

Information was obtained using a combination of existing reviews (e.g. Wheeler and Shaw, 1995), existing reference collections, books, library searches and library database searches in order to supplement existing reviews with more recent findings.

2.2.1 Search strategy

A set of keywords and phrases was compiled for use in scanning existing reviews and reference collections to highlight key sections or relevant papers. This existing set of information was then supplemented by establishing a set of search terms which were then used to search the range of available online databases for potentially relevant papers.

2.2.2 Search terms used

2.2.2.1 Keywords and phrases used

- Peat depth
- Peat stratigraphy
- Peat profiles
- Stratigraphic profiles
- Residual peat
- Establishment of bog vegetation
- Poor-fen
- Fen peat thickness
- Succession
- Transition zone

- Groundwater influence
- Sphagnum colonisation
- Mineral sub-soil
- Minimum peat depth
- Water quality
- Water chemistry
- Vertical water losses
- Enrichment
- Ombrotrophic peat
- Fen peat

2.2.2.2 Database search terms used

- Effect of remaining peat depth on bog restoration;
- Peat depth and Sphagnum restoration;
- Remaining peat deposit and vegetation recovery;
- Bog restoration and residual peat;
- Restoring bog, effects of underlying peat;
- Impact of peat depth on restored peatland plants;
- Peat depth and vegetation;
- Fen peat thickness
- Residual peat depth for bog restoration;
- Peat depth and Sphagnum restoration;
- Residual peat and vegetation recovery;
- Peat depth, raised bog, recovery, vegetation, harvest;
- Bog restoration.

2.2.3 Databases and search engines used

- Science Direct
- The Directory of Open Access Journals
- Google Scholar

2.2.4 Study inclusion/exclusion criteria

2.2.4.1 Relevant populations

- Included: ombrotrophic *Sphagnum* raised bog systems in temperate and boreal regions; poor fens associated with raised bog development and succession; raised bogs subject to commercial peat extraction, whether milled or sod-cut.
- Excluded: all other peatland systems; purely laboratory-based studies.

2.2.4.2 Intervention

- Included: depth of peat recorded in restoration site; thickness of fen peat layer; chemistry of peat/water recorded in restoration site; hydrological behaviour of restoration site recorded; physical behaviour of the residual peat on restoration site described; duration of fen phase in natural/restoration succession measured or estimated.
- Excluded: restoration studies where no information is given about residual peat depth; stratigraphic studies which give no indication of timescale for natural/restoration fen succession.

2.2.4.3 Comparison

- Included: All comparison studies relevant to restoration to ombrotrophic raised bog vegetation.

2.2.4.4 Outcome

- Included: All studies presenting outcomes relevant to restoration of ombrotrophic raised bog vegetation on commercially worked sites, including those studies which do not clearly define the nature of the vegetation obtained.

2.2.5 Selection of references for assessment

Numerous papers, books, chapters in books, and research reports identified through the use of the search terms were selected for assessment. These were then supplemented with publications identified by electronic searches. Search results were limited to the first five pages of results or to the first 50 hits for each search term. Papers were assessed for relevance on the basis of title and abstract. Those selected for more detailed assessment were first checked against the inclusion/exclusion criteria before being subject to critical appraisal.

2.3 Critical appraisal

The process of critical appraisal evaluated each selected publication in terms of the contribution it could make to shedding light on a given sub-question. The evaluation process consisted of three steps: categorisation, evaluation of relevance and evidence, then finally synthesis of the evidence from all relevant selected publications to determine the strength of that evidence in terms of providing a robust answer to the sub-question.

2.3.1 Categorisation of publications

Each publication was assigned to a category defining the type of study or description, the category being determined by its relevance to the particular sub-question under consideration. Three categories were employed, each with a rating designed to identify the degree of precision and robustness of the information presented (see Table 1).

Table 1. Rating system used for categorisation of publications

Rating	Description
3	Experimental study with field measurements; quantified site description; systematic critical review with independent verification of reviewed evidence
2	Review with quantified evidence; correlation study; quantified site information having indirect relevance to the sub-question
1	Review with no presented supporting evidence; narrative site report with only indirectly relevant information; opinion piece

2.3.2 Evaluation of publications

As there were few examples of quantified, replicated studies which could be assessed meaningfully on the basis of their experimental design, an evaluation was made of the quality, quantity and relevance of the evidence provided in relation to the sub-question under consideration. The evaluation categories can be seen in Table 2.

Table 2. Evaluation categories used to assess publications

Rating	Description
+++	Good supporting evidence
++	Moderate supporting evidence
+	Little supporting evidence

The publications were then individually scored for each sub-question and the results were collated. A narrative account of the various publications was also provided, highlighting the reasons for the various scoring decisions.

It is important to make clear that a single publication may be assigned different scores under different sub-questions because the nature of the information provided by any particular publication for one sub-question may be very different from the information provided in relation to another sub-question.

2.3.3 Synthesis of publications

The overall picture obtained from the assessment was then evaluated for the strength of evidence supporting the overall picture to emerge for each sub-question. The criteria used to measure the strength of evidence are set out in Table 3. Finally a further narrative account summarises the position reached for each sub-question.

Table 3. Strength of evidence emerging from the selected publications

Rating	Description
Strong	Consistency across publications; large number of results pointing to similar outcomes
Moderate	Mixed evidence emerging across publications but tendency towards particular outcomes
Weak	Little evidence or much very conflicting evidence with no clear outcomes

2.4 Integration of results

The implications of the results obtained for each sub-question were then integrated to provide an overall view in relation to the primary question. This integrated view is presented in the Discussion section of the present review.

3. RESULTS

Although the results for the individual sub-questions are addressed in turn below, it is helpful first to highlight a significant and important feature of the available evidence relevant to several of the sub-questions and, ultimately, to the primary question. Specifically, this concerns the scope of the evidence.

3.1 Scope of the evidence

As in all fields of scientific research, understanding of the processes which underpin peat bog restoration has evolved over time and, as often occurs in research, the centres of research activity have shifted from location to location over the years. In the 1970s and 1980s, Germany and the German peat industry represented one of the leading centres of peatland restoration research (e.g. Akkermann, 1982), along with an active research and conservation movement in the Netherlands. Additionally, the Dutch researchers initiated a major programme of conservation-focused research in the Republic of Ireland for the simple reason that there were no near-natural bogs left in the Netherlands to study (e.g. van der Schaaf. 2000). Alongside this Dutch initiative, Bord na Mona, the Irish Peat Development Board, had been conducting a series of restoration experiments – though not always with peatlands as the restoration target – on the extensive tracts of bog which had been industrially cut for electricity power generation and to supply the horticulture market. The Finnish peat industry has also long been active in promoting restoration research, particularly as Finland has often been in the vanguard of new developments in the peat extraction industry (e.g. Vasander, 1996; Sopo, 1998).

While some small-scale experimentation had earlier been undertaken on commercially worked peat bogs in Britain, particularly at Thorne Moors in Humberside, it was not until the end of the 1980s and start of the 1990s that major public concerns about the state of lowland peat bogs in Britain brought increasing pressure to bear on the commercial peat industry. This stimulated significant research activity devoted to the question of peatland restoration following commercial peat extraction, largely funded by the peat industry (e.g. Money, 1994; Heathwaite, 1995). At the same time, the UK Government set up the Peat Working Group (Department of the Environment, 1994) and established the review of restoration techniques (Wheeler and Shaw, 1995) referred to earlier. This review necessarily drew heavily on evidence gathered from Germany and the Netherlands. After this relatively short-lived period of academic research activity the main effort in the UK since then has fallen to NGO conservation bodies and the statutory conservation agencies, the main outputs from this work having been Stoneman and Brooks (1997), Parkyn, Stoneman and Ingram (1997) and Meade (2003). Relatively little of direct relevance to lowland raised bogs and commercial peat extraction has been published from UK research in the last decade or so.

In the late 1990s the global centre of restoration research shifted to Canada where a major programme of research was initiated into the restoration of peat bogs which have been subject to commercial peat extraction. This on-going programme of industry-funded research has produced numerous research papers and various guidance documents, setting out what is currently understood as optimal conditions and actions required for successful restoration of peatlands following the cessation of commercial working (e.g. Quinty and Rochefort, 2003; McCarter and Price, 2013).

An additional stimulus for restoration research has emerged in recent years with the legal obligations placed on EU Member States (MS) by the EU Habitats Directive. With both 'active raised bogs' and 'degraded raised bogs capable of natural recovery' listed as habitats of EU concern under Annex 1 of the Directive, MS are now obliged to carry out national inventories of Annex 1 habitats, report on their condition and demonstrate that restoration actions are bringing about improvement in the condition of those examples which are currently in poor condition. In particular, 'degraded raised bogs' are expected to be restored to an 'actively growing' state within 30 years. While this time-frame only places legal obligations on MS for those sites which are designated as Special Areas for Conservation (SAC), there is nevertheless a wider obligation for all examples of habitats listed under Annex 1 to be brought into 'favourable condition'. Consequently this has focused MS attention on techniques which can provide some degree of confidence that raised bogs which have been subject to commercial peat extraction can be restored to an active state with peat bog vegetation sooner rather than later (e.g. Triisberg *et al.,* 2014).

One result of these various geographical shifts in restoration research is that relatively little published information exists for the restoration of cut-over peat bogs in the UK. Apart from research undertaken in Ireland, the main centres of restoration research lie in regions which have a distinctly different climate regime from the UK, in being markedly more continental and experiencing more severe winters than is typical for the UK. Its more oceanic climate means that the UK has a longer growing season than these continental areas, and generally has more, and more regular, rainfall, all of which favour *Sphagnum* growth. Nonetheless it is necessary to exercise a degree of caution about applying results from Canada or Finland to UK conditions. That said, there is a sufficiently encouraging level of consistency in the results obtained from these various research programmes to give some confidence that results from such regions can reasonably (albeit with some caution) be applied to UK sites and conditions.

3.2 Results of the searches and selection of publications for detailed review

The library and reference collection searches provided a number of relevant publications for detailed assessment. The database searches meanwhile identified a total of 634,695 hits across all the search terms, although as stated earlier, for reasons of practicality only the first 5 pages of hits, or the first 50 hits, whichever was the larger, were then examined for title and abstract. From these various sources, a total of 85 papers were finally selected for detailed assessment. The tables of hits for each database, and papers identified for further scrutiny, are presented in Annex 1 and Annexes 2 - 7 respectively.

The relatively small number of publications finally selected perhaps reflects the limited number of occasions where studies of cut-over bogs have included measurements of the residual peat depth or parameters relevant to that factor. While there is a wide range of publications which describe the recovery of vegetation within former peat-extraction areas, if no indication is given of the initial residual peat depth then the publication only has potential relevance to Sub-Question 1 (and only then provided the fen-peat thickness is recorded) or Sub-Question 5 (if some indication is given of timing for development from fen to bog vegetation).

It is also interesting to note that until recently much dating of stratigraphic profiles in undisturbed peat bogs has tended not to focus on the duration of the transitional phase during which any fen community at the base of a peat profile is replaced by ombrotrophic bog vegetation. There has generally been much greater interest in the rate at which bog peat has accumulated over time. This is largely, one must assume, because the timescale over which bog peat has accumulated is much greater than the fen phase and therefore more climatic shifts are recorded (and more carbon is stored) within the column of bog peat.

3.3 Sub-Question 1: What is the typical thickness of the fen-peat layer in a lowland raised bog?

3.3.1 Background

Commercial peat extraction and associated planning consents commonly set limits to the thickness of peat which must be left in the ground at the end of commercial operations. In the UK it is often not the quality of the peat which influences the decision to limit the operation depth. More usually these limits are imposed by operational or commercial practicalities – for example when the extraction machinery begins in places to dig into the mineral sub-soil. In general, therefore, little consideration is given to the fact that the lower peat deposits may differ substantially from those in the upper part of the peat profile and consequently relatively little effort is put into identifying the presence and characteristics of such a layer.

A few restoration programmes on cut-over raised bogs have been concerned to identify the nature of the surface on which the restoration work will be undertaken, while numerous studies of natural raised bogs have generated information about the nature of the peat column and the presence of such fen layers. Consequently it is possible to establish whether there is a consistent pattern to the presence (or absence), depth and extent of such a layer forming the basal peat deposits in lowland raised bogs.

3.3.2 Categorisation and assessment

A total of 20 publications from the selected collection provided information about the thickness of a fen-peat layer beneath the ombrotrophic peat of a raised bog. Although not all publications were themselves measured field studies or quantitative descriptive papers, the diagrams presented gave measured values or scaled diagrams based on field data and were thus classed as robust 3+++ information. The individual authors and their associated values for fen-peat thickness are presented in Table 4.

3.3.3 Synthesis

There is **Strong** evidence to show that a layer of fen peat at least 1 m thick underlies many, if not most, lowland raised bogs with a tendency to a depth of around 1.9 m, although in some cases the depth of fen peat exceeds 3.0 m.

Some parts of a raised bog may not have any underlying layer of fen peat, particularly where paludification has extended the bog across formerly dry land (e.g. Wheeler and Shaw, 1995, their Fig 1.1D) while some sites appear to have no fen layer at all (e.g. Wheeler and Shaw, 1995, their Fig 1.1C). Nonetheless the evidence strongly suggests that it would be reasonable to assume the presence of a fen-peat layer of *at least* 1.0 m thick beneath the major part of most lowland raised bogs in the UK. Confirmation of such a layer for any given site, and the nature of the layer across the site, would require field sampling because it cannot be predicted from any surface features.

The presence of a fen layer may thus tend to skew the progress of bog restoration towards poor-fen communities on sites where the residual peat surface lies within this fen peat layer. Water chemistry is the most obvious way in which the presence of fen peat might skew vegetation development towards fen vegetation rather than ombrotrophic bog vegetation. The possible influence on water chemistry of a residual peat layer, particularly one which contains only fen peat, forms the focus of the next sub-question.

Table 4. Depths of fen peat at the base of raised bogs, taken from data tables or from scaled drawings of bog profiles (with source figure/page number indicated). For a single site, if more than one measurement is available (for example at the margins and in the centre) the greatest thickness has been taken. In cases where the authors provide a value for fen-peat thickness, this is rarely if ever accompanied by an indication of whether the value is an average or a maximum/minimum depth. For publications giving data for more than three sites, the values have been averaged across the sites. Wind-Mulder et al. (1996) give only total residual peat depth for their four cut-over sites and state that three of these sites resembled fen. They also give ranges for two of these fen sites so the averaged minimum value from their ranges is conservatively taken for these 'fen' (originally raised bog) sites.

Author	Depth of fen peat (m)
Bartley *et al.* (1990)	2.2
Clymo 1983 (Fig. 4.12)	1.68
Gorham (1949)	1.5
Hughes and Barber 2003 (Fig. 2)	3.0
Hughes and Barber 2004 (Table 2)	1.6
Hughes *et al.* 2000 (Fig. 3)	1.56
Karofeld *et al.* 2015	1.5
Kivimäki *et al.* 2008	>1.0
Lode and Ilomets 1998	0.85
Loisel and Yu 2013a (average of 4 sites)	3.62
Malloy and Price 2014	1.0
Moore and Bellamy 1974 (p.147)	1.52
Ruuhijärvi 1983 (Fig. 2.4B)	1.67
Rydin and Jeglum 2006 (Fig. 7.5)	1.25
Sliva *et al.* 1997 (Fig. 32.4)	4.5
Succow and Jeschke 1990 (p.66)	2.67
Tansley 1939 (Table XXI)	3.25
Tansley 1939 (Table XXII)	4.25
Turner 1970 (p.101)	3.4
Wheeler and Shaw 1995 (Fig. 1.1B)	0.0
Wheeler and Shaw 1995 (Fig. 1.1C)	0.0
Wheeler and Shaw 1995 (Fig.1.1D)	1.7
Wind-Mulder *et al.* 1996	>0.71
Average fen thickness	>1.93

3.4 Sub-Question 2: Does residual peat depth influence surface-water chemistry and bog restoration?

3.4.1 Background

Some of the earliest formal scientific distinctions made between 'bog' and 'fen' in the UK were based on water chemistry. Thus Tansley (1939, p.634) defined fens as areas of waterlogged organic soils where the peat was "*somewhat or decidedly alkaline, nearly neutral, or somewhat, but not extremely, acid*" whereas he regarded bogs as consisting of peat "*which is extremely acid*". In contrast, Du Rietz (1954) proposed the terms 'minerotrophic' (groundwater fed) and 'ombrotrophic' (rain fed), thereby separating peatland systems into groundwater-fed fens and rain-fed bogs on the basis of the water supply rather than water chemistry. This separation provides a clear *functional* difference between fens and bogs, in the sense that fen water supplies can be influenced by activities within the catchment whereas the supply of rain to bogs cannot.

In the UK, however, Du Rietz's focus on water source (Du Rietz, 1954) is not reflected in a similarly clear separation on the basis of water chemistry. This is because all parts of the UK are affected by blown sea-spray. Consequently the chemical composition of rainwater in the UK varies from west to east but is everywhere distinctly more solute-rich than rainfall in, for example, Finland. Industrial pollution has also played a part in altering the chemical composition of UK rainwater. As a result, the dominant species of *Sphagnum* now found on UK bogs – *Sphagnum papillosum* – is considered to be a fen species in Sweden and Finland (e.g. Sjörs, 1983, p. 79; Ruuhijärvi, 1983, p. 65). This does not mean that UK bogs are minerotrophic. In Du Rietz's concept UK bogs are still ombrotrophic, albeit fed by somewhat enriched precipitation, while UK minerotrophic fens are further enriched by the added inputs from the catchment (Proctor, 1992). The whole chemical signature of UK peatlands is therefore shifted somewhat towards a mineral-enriched state compared to more continental parts of Europe. This chemical shift does, however, raise the question of how to define water chemistry which is suitable for 'restoration to bog' rather than restoration to something more closely resembling solute-poor fen. Fortunately in terms of botanical response and peatland ecosystem functioning the distinction remains reasonably clear because the issue is not determined by *absolute* values of chemical composition but instead by *relative* values. Thus while a raised bog in the UK may be chemically richer than a raised bog in Finland, the ombrotrophic dome of the UK bog is still markedly more acidic and poor in solutes than the fen margin where the solutes accumulate and become concentrated *relative to* the water on the bog dome. This distinction is mirrored in the vegetation, where, for example, the place of *Sphagnum papillosum* in the fen margins of Finnish bogs is taken in the UK by *S. palustre*, which only occurs in the far south of Finland (Daniels and Eddy, 1985).

Absolute chemical signatures for 'fen' and 'bog' must therefore be treated with caution, but for any given regional locality it is still generally possible to distinguish local 'fen' conditions from those which are more characteristic of the local 'bog' environment, as shown by Waughman (1980) for a series of German peatland systems located south of Munich. Consequently it is valid to compare studies from different regions even though the chemical signature for 'fen' in one region may overlap somewhat with the signature for 'bog' in another, because the functional differences between the two ecosystem types still exist in each region. Thus pH values for fens and bogs in the European part of the former USSR and values for similar communities in the UK are shown in Table 5, highlighting both the differences between regions and the continued distinction between fen and bog within a single region.

The overall chemical boundary between fens and bogs has nevertheless been the subject of ongoing discussion in recent years. Wheeler and Proctor (2000) argue that the main means of separation between peatland systems should be pH and 'fertility (i.e. availability of N and

P) and question the utility and reliability of a separation based on the concept of minerotrophic and ombrotrophic water supplies. Økland *et al.* (2001) have responded with the counter argument that in any given region the distinction between minerotrophic conditions ('the mineral soil water limit') and ombrotrophic conditions is more sharply defined by a combination of hydrological, chemical and botanical factors than either pH or fertility and provides the most reliable form of boundary.

The difference between these approaches, and the possible confusions that arise when using a chemical signature as the means of separation, are highlighted by various examples from published literature. Thus, Tansley (1939) identified three types of 'bog' when describing UK and Irish vegetation types: 'raised bog', 'blanket bog' and 'valley bog'. Tansley (1939) defined valley bogs as 'bog' because those in the south of England in particular are formed over extremely solute-poor Greensand rocks and are therefore relatively acidic environments. Du Rietz's system (Du Rietz, 1954) would, in contrast, define valley 'bogs' as minerotrophic fens and thus make a clear distinction between such systems and the purely precipitation-fed raised bogs and blanket bogs. Tansley's use of the term 'bog' for these catchment-dependent systems has led to considerable confusion about, and occasional inappropriate management of, such minerotrophic valley mire systems. Proctor (1992), meanwhile, demonstrates through a large-scale study of water chemistry in British and Irish peatlands that Tansley's (1939) 'valley bogs' (though functionally minerotrophic fens) in the south of England do indeed overlap in their chemistry with at least some truly ombrotrophic bogs, particularly bogs in the west of Ireland. Daniels (1978) highlights this same overlap in a review of British and Irish peatland vegetation, while Waughman (1980) shows a similar chemical overlap for a complex of peatland systems in southern Germany. All these authors nevertheless use the concepts of ombrotrophic (or ombrogenous) bog and minerotrophic fen to distinguish their peatland types. Gorham (1949), Daniels (1978), Waughman (1980), Proctor (1992) and Nakamura *et al.* (2002) provide pH and other chemical data for a wide range of natural temperate or boreal peatlands, both ombrotrophic and minerotrophic, and thus provide the context for an assessment of the relationship between residual peat depth and water chemistry in cut-over raised bogs. A wide geographical spread of values for pH and conductivity is presented in Table 5.

Table 5. Typical range of pH values for fen, poor-fen ('transitional' mire) and bog in three widely separated regions – the European part of the former USSR (Tarnocai and Stolbovoy 2006), Alberta, Canada (Rydin and Jeglum 2006) and the UK (Wheeler and Shaw 1995) plus conductivity values for Canadian raised bog waters (Rydin and Jeglum 2006), (Langlois et al. 2015).

	pH		
Region	Fen	Poor-fen	Bog
European part of former USSR	5.3-4.8	4.6-3.9	3.6-3.2
Alberta, Canada	6.88-6.28	5.38	3.96
UK	8.0-5.0	6.0-4.0	<4.5
	Conductivity µS cm^{-1}		
Alberta, Canada	187-91	48	39
New Brunswick, Canada	105*	51**	32

*'lagg fen at edge of raised bog **actually lower slopes of 'rand' (sloping bog margin)

Some restoration studies considered by the present review measure water chemistry in order to characterise sites (and thereby distinguish between bog and fen) while others infer water chemistry from the composition of the vegetation in the manner proposed by Økland *et al.* (2001). For the purposes of the present Sub-Question, only those studies which provide actual water chemistry data will be considered, although such studies may additionally use the vegetation to identify local 'bog' and 'fen' conditions. Studies which provide no chemical data but instead use vegetation alone will be considered in Sub-Question 4.

3.4.2 Categorisation and assessment

Information relevant to this Sub-Question was examined in detail for 20 publications. Of these 20 publications, 11 were experimental studies or quantified field descriptions which provide measured values for water or peat chemistry relatable to peat depth and were thus categorised as 3+++. Some papers which did provide measured hydro-chemical and peat-depth data only examined block-cut peatlands and may therefore not appear so directly relevant to the current question of required residual peat depth. They are nevertheless relevant to the question of residual depth beneath the bases of drains and were therefore also categorised as 3+++. Three papers measured water chemistry but did not give explicit measurements of peat depth. These papers were categorised as 3+. One paper provided information linking pH to vegetation types and, because the peat depth information was provided in two other reviewed papers, this was given a score of 2++. Similar reliance on other sources for key information, or a lack of clarity in the source of the water chemistry, meant that two other papers were also given a score of 2++. The three remaining publications were reviews, one of which provided some limited quantified data collated from other publications and was thus categorised as 2++ while the second review publication simply provided guidance values though supported by a range of cited literature and was thus categorised as 2+, and the last review provided no directly supporting evidence and was thus classed as 1+.

Gorham (1949) [3+++] gives measured values from a raised bog in South Cumbria for the chemical differences between the fen peat at the base and the ombrotrophic peat higher in the peat column. The fen peat was measured as pH4.83 and has a depth of 1.5 m, while the bog peat ranged from pH3.84-4.49. The fen peat had an electrical conductivity of 118.5 µS compared to 86-105µS recorded from the bog peat, while the fen peat had 2-3x the concentration of calcium. Looking at the question from a different perspective, Langlois *et al.* (2015) [3+] characterise the chemistry of the open bog, the marginal rand slope and the surrounding lagg fen along 10 transects on 6 raised bogs in New Brunswick. Unfortunately they give no measured peat depths. It might be assumed that the chemistry of the present lagg fen may give an indication of the prevailing chemical conditions when the basal fen formed, but this is by no means certain. They record pH3.73-3.85 and 20-32 µS for conductivity for the bog expanse, pH3.76-3.96 and 14-51 µS conductivity for the sloping rand margin, and pH4.2-4.78 and conductivity of 52-105 µS for the lagg fen. Wilhelm *et al.* (2015) [3+++] meanwhile record pH5.63 and conductivity of 20.7 µS for a poor fen site in Ontario with 3.9 M of peat, reflecting the potential variability in conductivity encountered in such sites.

Smolders *et al.* (2003) [3+] give a measured range of pH values (pH4 to around pH6.7) for a range of sites after industrial working, but these values are not accompanied by measured residual peat depths. Sliva *et al.* (1997) [3+++] and Sliva and Pfadenhauer (1999) [3+++] give pH and conductivity for a transect along a milled field ('Field 6') on a raised bog in southern Germany, described (and illustrated with a profile diagram) as having 0.5 m residual bog peat sitting on a layer of transitional peat which is exposed at the western end of the site. The average pH along the transect ranges from around pH4 to pH7 while the conductivity ranges from around 20 µS to 450 µS, and these high values are recorded from the middle of the transect rather than the somewhat enriched western end, a fact attributed to groundwater inundating parts of the bog-peat surface. Maas and Poschlod (1991) [2++] present data from the same site (Kendlmühlfilzen) and show that *Eriophorum vaginatum* grows well only in those areas with a pH between pH3.75 and pH4.25. It is also stated that *E. vaginatum*, *Calluna vulgaris* and *Rhynchospora alba* depend on raised bog peat to grow vigorously. Konvalinkova and Prach (2014) [3+++] give measured data for 11 milled raised bogs in the Czech Republic. The peat depths range from 0-1 m but average across the bogs at 0.56 m. The surface water varies from pH3.8 to pH7.3 while the peat varies from pH3.8 to pH5.7. Electrical conductivity ranges from 46-373 µS. Tuittila *et al.* (2000) [2++] studied the restoration response shown by part of a milled field in Finland which had, at the start of their study, an average residual peat thickness of 0.76 m. Though they do not give pH values for the peat in the experimental area, water with a pH range of pH5.1 to pH 6.0 from the surrounding peatland (which nowhere had a thickness greater than 1 m) was used to re-wet the experimental plot. Money (1994) [3+++] and Money (1995) [3+] presents measured values for cations and anions from milled fields at Thorne Moors, Humberside, and describes these values as “resembling poor-fen rather than ombrotrophic bog”, but he also provides pH values of between pH3 and pH3.7 for the milled fields, which is markedly more acidic than most natural bog waters in the UK and Money (1994) gives peat depths, pH and conductivity for the study area as well as for a wide range of other cut-over sites . Money (1995) notes that poor-fen chemistry was also recorded from another cut-over area with “several metres of peat remaining” (though provides no depth data), and speculates that this chemical enrichment may be due to water from the sub-soil or may simply result from decomposition of the surface peat. That said, the construction and regular use by heavy machinery of a limestone road across the site may also contribute to the elevated levels of calcium (Money 1994).

Studies carried out on cut-over sites in Canada include examples of both block-cut and milled peatlands. The relevance of block-cut sites is that the trenches potentially give some indication of the environment which may prevail in larger drains and the smaller ditches which delimit milling ‘fields’ on a milled site. For example Gonzáles *et al.* (2014) [3+++] surveyed 6 block-cut peatlands in Quebec for spontaneous vegetation recovery in the trenches and residual peat depths of 1 – 1.82 m were associated with pH values of pH3.5 to pH4 and conductivity values of 43-81 µS. Interestingly the lowest pH and conductivity values were not associated with the deepest thicknesses of residual peat. Girard *et al.* (2002) [3+++] investigated a total of 26 trenches cut in a block-cut site in Cacouna Bog, Quebec, for which the range of average residual peat depths was 1.39-3.89 m. These depths were associated with pH values ranging from pH3.5 to pH4.9, and in this case the shallowest residual peat depth was associated with the highest pH and the deepest residual peat depth with the lowest pH. Wind-Mulder *et al.* (1996) [3+++] surveyed three milled sites and one block-cut peatland distributed across Canada. The milled sites had residual peat depths which ranged from 0.4-4 m although the average was approximately 1.4 m, while the block-cut site had a residual peat depth of 2.5-3 m. The pH of all sites lay between pH3.7-3.9, while for three sites the conductivity ranged from 30 µS to 97 µS, with the site having the deepest layer of residual peat mid-way between these values. What they did find, however, was that values for pH, conductivity and a range of cations and anions in the cut-over sites were generally substantially higher than values obtained for undisturbed sites and that the block-cut site, with the deepest residual peat layer, tended to be the most similar to undisturbed values. Poulin *et al.* (2005) [3+++] undertook a large-scale survey of 26 abandoned industrial peat sites across Quebec and New Brunswick, sampling 2,571 trenches and 2,595 baulks on block-cut peatlands and 395 milled peat fields. Chemical data were obtained for 105 trenches, 96 baulks and 34 milling fields. The average residual peat depth for the trenches was 3 m, associated with an average pH value of ph3.9 and a conductivity of 7.4 µS. For the baulks the average residual peat depth was 3.7 m with an average pH value of pH3.6 and conductivity of 9.3 µS. The milled fields had an average residual peat depth pf 1.7 m, an average pH value of pH 3.7 and conductivity of 50.3 µS. Poulin *et al.* (2013) [2++] describe restoration studies carried out on Bois des Bel in Quebec and note (from other sources) that the pH of surface waters on the restored area of Bois des Bel ranges from pH4.5 to pH6. Meanwhile other papers (e.g. McCarter and Price 2013) give the residual peat depth as 1.7 m. Malloy and Price (2014) [3+++] give measured values for another site in Quebec (Bic-Saint-Fabien) which is described as having been milled down to the fen-peat layer. The residual peat depth is 0.4 - >1 m, and the pH of surface waters is given as ph6.5 to pH7.

Wheeler and Shaw (1995) [2++] reviewed the information available at the time concerning the chemical characteristics of bogs, fens and cut-over bogs, also providing a small amount of unpublished data. As with the results obtained by Wind-Mulder *et al.* (1996) and already presented above, Wheeler and Shaw (1995) note that a range of data obtained for the cut-over areas of Thorne Moors, Humberside, and Danes Moss, Cheshire, display a marked chemical enrichment compared to natural bog waters. They also state [their Box 3.2 and their Table 6.c] that if fen peat is exposed then poor fen is likely to develop, although it has the potential then to develop into ombrotrophic bog subsequently. They also observe in relation to assessing the potential and range of options available for restoration that: "One of the most important considerations is whether the exposed peat is ombrotrophic (bog) peat or minerotrophic (fen) peat."

Quinty and Rochefort (2003) [1++] review the understanding of peatland restoration prevailing at that time. They do not present any chemical measurements but they specify thresholds for a decision to establish a bog restoration programme rather than one geared to fen restoration. The recommended threshold for Canadian sites is for surface-water pH to be <pH5.0 with a conductivity below 100 µS cm^{-1}. They also note that once extraction has exposed the basal fen peat then it may be advisable to consider fen restoration rather than attempting to restore bog, at least initially, and that a decision about which restoration route to follow should be determined by analysis of the peat chemistry and botanical composition.

Gorham and Rochefort (2003) [1+] also review the process of peatland restoration after industrial peat extraction. They do not provide any values for peat chemistry but note that where the peat has been mined to a depth which exposes earlier stages of peatland development, it is necessary to begin again from minerotrophic conditions and rely on natural succession for restoration success.

3.4.3 Synthesis

It is possible to draw together those data from the literature which provide values for peat depth, surface-water pH and conductivity. In general these data come from differing sites and thus express the generality of the pattern across a range of sites, although in some cases the data are also obtained for differing compartments within the same site. Not all of these datasets provide conductivity measurements, but all datasets used gave peat depth and surface-water pH. There are thus more data points for the relationship between residual peat depth and surface-water pH than there are for the relationship between residual peat depth and conductivity. In all, it was possible to use data provided by eight of the publications listed above to relate residual peat depth to surface-water pH (Konvalinkova and Prach, 2014; Money, 1994; Gonzáles *et al.,* 2014; Girard *et al.,* 2002, Wind-Mulder *et al.*, 1996; Poulin *et al.,* 2005; Poulin *et al.,* 2013; Malloy and Price, 2014) and five publications for residual peat depth and conductivity (Konvalinkova and Prach, 2014; Money, 1994; Gonzáles *et al.,* 2014; Wind-Mulder *et al.,* 1996; Poulin *et al.,* 2005). The remaining publications did not provide a suitable measure of residual peat depth.

The relationship between residual peat depth and surface-water pH can be seen in Figure 2. Three things in particular are worth highlighting. Firstly, there is a reasonably good relationship between the two factors, with a suggestion of a sharper rise in pH as the peat becomes so thin that the underlying mineral ground begins to have a marked influence.

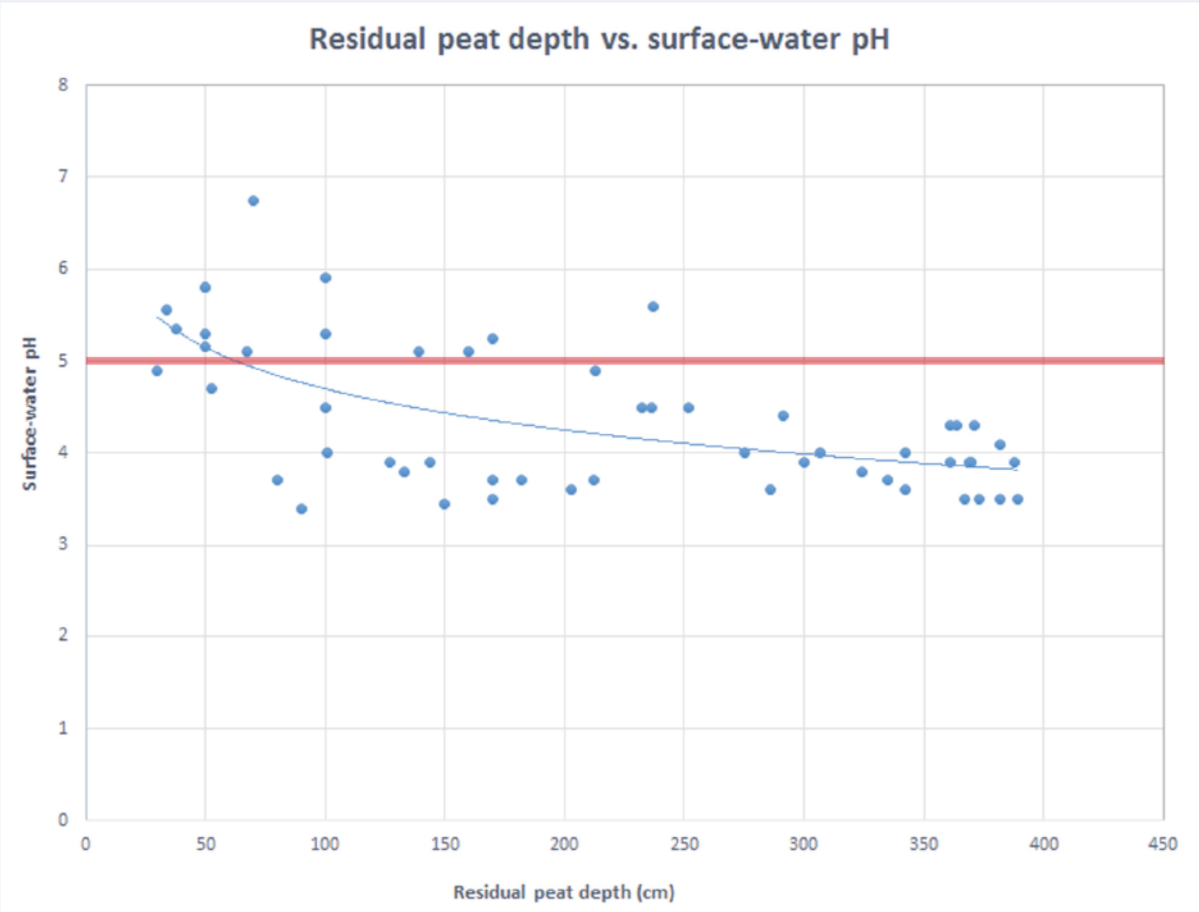


Figure 2. Surface-water pH and residual peat depth based on published data for a range of sites across Europe and Canada. A logarithmic trend line has been added. The red horizontal line marks the pH threshold which Quinty and Rochefort (2003) recommend as the boundary between sites which should have ombrotrophic bog as their restoration objective (less than pH5) and those which should seek to establish fen vegetation (more than pH5). Once the residual peat depth is less than 2.5 m, several examples are recorded of sites with pH greater than pH5. Almost all examples exceed pH5 when the residual peat depth is 0.5 m or less. Data derived from Konvalinkova and Prach (2014), Money (1994), Gonzáles et al. (2014), Girard et al. (2002), Wind-Mulder et al. (1996), Poulin et al. (2005), Poulin et al. 2013, Malloy and Price (2014).

Secondly, Quinty and Rochefort (2003) recommend that a threshold of pH5 is used to guide decisions about restoration objectives. If surface waters are less than pH5 then the restoration objective can be ombrotrophic bog, whereas if the pH is greater than pH5 then the restoration objective should be fen. Placing this threshold onto the plot reveals that a residual peat depth of somewhat more than 0.5 m may well be the absolute minimum required if ombrotrophic bog is to be the restoration objective. Thirdly, however, it is clear that there are many sites with a much greater residual peat depth which have a pH which is above the recommended threshold. It is only when there is a residual peat depth of more than 2.5 m that all examples lie within the recommended pH range for ombrotrophic bog restoration.

In the case of residual peat depth and conductivity, Table 3 shows that there is also a reasonable relationship, though it becomes more diffuse and displays an increasingly wide range of values, with in some cases a steep rise in conductivity, as the peat becomes so thin that the underlying mineral ground begins to have a major influence on water chemistry. Quinty and Rochefort (2003) also provide a threshold value for conductivity, recommending that if conductivity is greater than 100 μS cm^{-1} then restoration objectives should be directed towards fen restoration, while restoration to ombrotrophic bog should only be attempted if conductivity is less than 100 μS cm^{-1}. It can be seen from Figure 3 that once the residual layer of peat is less than 1 m, almost all sites have a conductivity which is more suitable for fen restoration. At least one example lies well above the threshold at 1.5 m. Only with a residual peat depth of greater than 1.5 m are all sites consistently below this threshold.

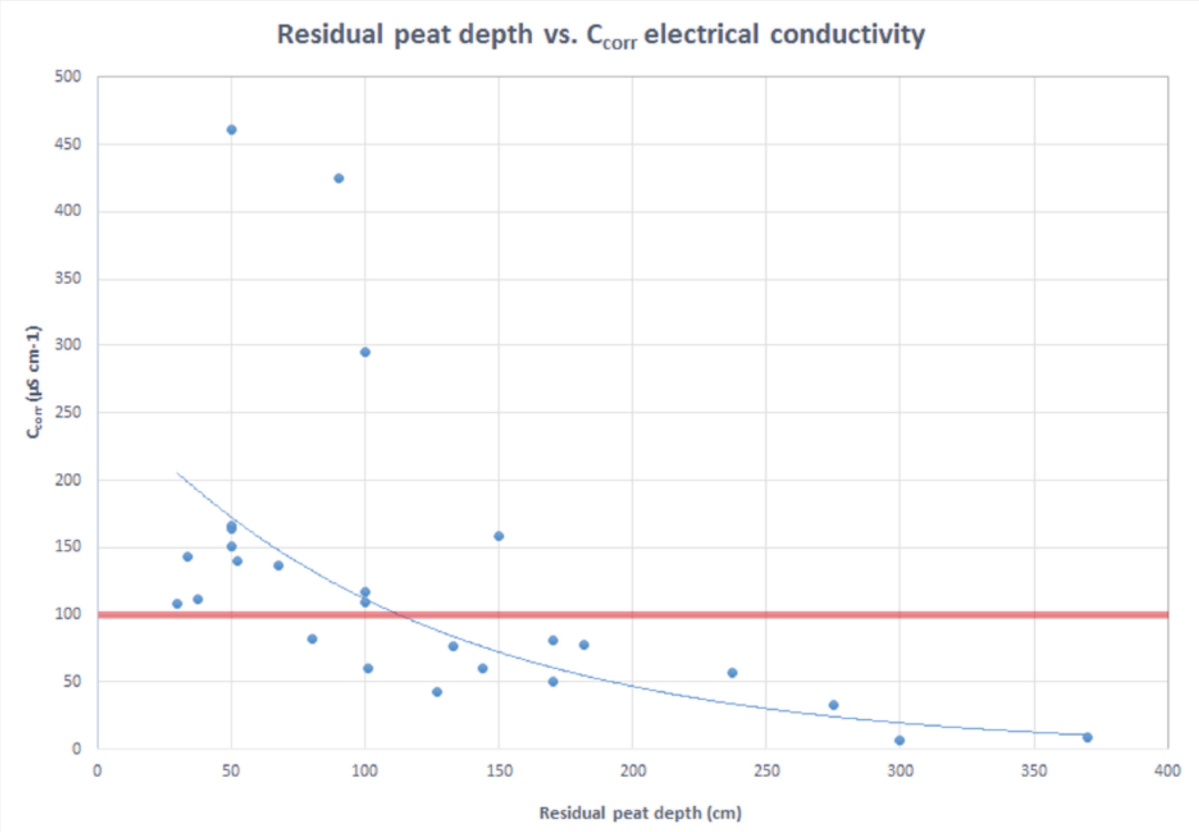


Figure 3. Surface-water conductivity and residual peat depth based on published data for a range of sites across Europe and Canada. An exponential trend line has been added. The red horizontal line marks the conductivity threshold which Quinty and Rochefort (2003) recommend as the boundary between sites which should have ombrotrophic bog as their restoration objective (less than 100 μS cm^{-1}) and those which should seek to establish fen vegetation (more than 100 μS cm^{-1}). Once the residual peat depth is less than 1.5 m, several examples of sites occur with conductivity greater than 100 μS cm^{-1}. Almost all examples exceed 100 μS cm^{-1} when the residual peat depth is 1 m or less. Data derived from Konvalinkova and Prach (2014), Money (1994), Gonzáles et al. (2013), Wind-Mulder et al. (1996), Poulin et al. (2005).

The data used to produce Figure 2 and Figure 3 are considered to be robust field measurements. It would be interesting to obtain the raw data from several other publications identified during the course of the present review to see what effect additional data would have on these two curves, but there is little to suggest from the other literature reviewed either in this Sub-Question or in other Sub-Questions to suggest that the nature of the curves is likely to change substantially if such an exercise were undertaken.

It is therefore concluded that:

- there is **strong** evidence of a clear relationship between residual peat depth and surface-water pH;

- there is **strong** evidence to show that *at least* 0.5 m of residual peat must remain as a minimum across a site if the restoration objective is to be ombrotrophic bog;
- indeed there is **strong** evidence to suggest that if ombrotrophic bog is to be the restoration objective, the combined effects of pH and conductivity indicate a requirement for a residual peat layer which is at least 1.5-2.5 m deep to remain when commercial extraction ceases.

3.5 Sub-Question 3: Does residual peat depth influence the hydrology of bog restoration?

3.5.1 Background

As Moore (1987) makes clear, and has already been discussed in the previous Sub-Question, there is a broadly accepted consensus that peatland ecosystems can be separated into two rather distinct types – ombrotrophic bogs and minerotrophic fens. If a peatland which has been subject to industrial peat extraction is to be restored to an ombrotrophic bog, rather than to fen which may then become bog, it is evident that the starting point cannot be a minerotrophic system. Consequently there is general agreement that a thickness of peat must remain at cessation of extraction operations in order to insulate the new bog vegetation from groundwater influences – because if it were subject to such influences then by definition the restored habitat would be fen rather than bog.

For many decades now the standard approach to restoration after industrial peat cutting has been to leave a certain thickness of 'strongly-humified peat' as a basal layer which then forms the starting-point for restoration of a peatland ecosystem. Thus Eggelsmann (1982) states that a [translated from the German.]: "*black (humified) peat layer should everywhere have a minimum thickness of 0.5 m.*" This basic principle been echoed by a range of authorities ever since, including Blankenburg and Kuntze (1987), Schouwenaars (1993a), Wheeler and Shaw (1995) and Quinty and Rochefort (2003), and continues to appear in various forms within current planning consents. In fact Eggelsmann (1982) sets out certain other requirements which will be considered later, while Schouwenaars (1993a) qualifies this simple condition by recommending that the residual thickness should be adjusted to suit the character of the basal peat layer, with a basal layer of at least 50 cm being required for hydrological purposes in the case of highly humified peat with a von Post value of >/=H7, whereas peat with a lower von Post value may require 1 m or more as the basal layer. The von Post test is the standard means of testing the state of decomposition (termed 'humification'). The test is performed on freshly-sampled peat and is designed as a simple rapid test to be carried out in the field. By squeezing a sample in the hand and observing the result, it is possible to assign the sample to a degree of humification on the von Post scale. This scale ranges from H0 to H10, with H0 being the least decomposed/humified peat and H10 being the most humified.

In order to understand the hydrological implications of leaving any thickness of industrially-mined peat as a base for peat bog restoration, it is important to be clear about the nature of the peatland system being mined, the hydrological processes which characterise a peat bog system, and the consequent nature of any residual layer which remains at the end of industrial operations.

3.5.1.1 The 'diplotelmic' bog – the 2-layered structure of a raised bog

The raised bog which forms as a result of the processes illustrated in Figure 1 consists of a very large mound of waterlogged, semi-decomposed plant material to which yet more material is constantly being added by the living layer of *Sphagnum* bog moss. In practice this living layer does more than simply add fresh material to the accumulating mound of peat. The living surface – termed the 'acrotelm' – of the bog acts as a regulator or mediator between the accumulated body of peat – termed the 'catotelm' – and the outside world. The living acrotelm is very thin, only perhaps 0.3-0.4 m deep, compared to the 9-10 m thickness of peat stored in the catotelm but this enormous quantity of peat could not have accumulated without the acrotelm. Indeed the peat of the catotelm, built up over millennial timescales, will start to be lost if the living acrotelm is removed, as indeed it is when a raised bog is industrially mined for its store of peat.

3.5.1.2 The nature and function of the acrotelm

A typical raised bog acrotelm consists of a living *Sphagnum* bog moss carpet within which a range of other plant species grow, much as plants grow in the uppermost part of a mineral soil but in this case there is no soil, only waterlogged semi-decayed moss which is too hostile an environment for most plants. A relatively specialised assemblage of plant species therefore tends to be associated with such *Sphagnum*-dominated surfaces, many of them relatively shallow rooted because the lower part of the acrotelm is constantly waterlogged and there is little in the way of nutrition in the catotelm peat beneath.

The *Sphagnum* carpet has some interesting properties, not least of which being its capacity to moderate water flow and thus provide a relatively constant 'drip-feed' of water to the catotelm beneath despite sometimes highly variable periods and amounts of rainfall – or more accurately, precipitation, because water inputs can also be in the form of snow, as well as mist, fog and dew ('occult precipitation'). The acrotelm is able to achieve this controlled flow because of its structure. Just beneath the tightly-packed heads of *Sphagnum* the individual plants have a stem with a series of 'spreading' and hanging 'pendant' branches covered with small water-absorbing leaves. The spreading branches result in an open scaffolding structure while the pendant branches draw water up the stem (which has no water-transport tissue itself) to keep the heads of the *Sphagnum* supplied with sufficient moisture when it is not raining. This open scaffolding permits relatively easy movement of water both vertically and laterally. In heavy rainstorms the excess water is therefore able to move fairly rapidly through the upper layer of the acrotelm and drain away.

Some 10 cm down into the acrotelm the plants become pressed more tightly together by the weight of the plant material above and some branches are dying so they begin to collapse and fragment. This slightly denser matrix is more resistant to water movement and so after a period with no rain when the water table falls into this somewhat denser layer, water movement is more difficult and so the acrotelm is able to retain a quantity of water from previous rain events (see Figure 4).

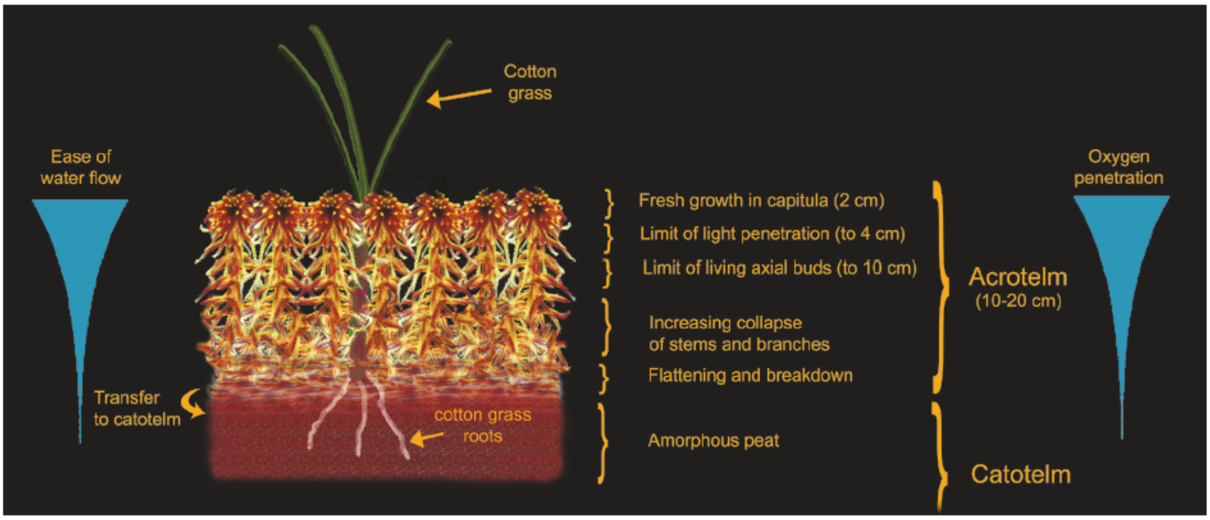


Figure 4. Structure and characteristics of a Sphagnum-dominated raised bog acrotelm. Reprinted from Lindsay, R. 2010. Peatbogs and carbon: a critical synthesis to inform policy development in oceanic peat bog conservation and restoration in the context of climate change. Edinburgh: RSPB.

Even deeper into the acrotelm, around 20-30 cm, much of the *Sphagnum* is now dead and breaking up into smaller and smaller fragments which are increasingly compressed together by the weight of material above. Water movement through this material is now extremely slow, and if there is a prolonged period without rain the *Sphagnum* carpet will even shrink slightly, thus compressing the lower material even more and thus further reducing water flow. In this way the acrotelm always has some water in reserve which it can pass on very slowly and steadily to the catotelm, thereby maintaining the catotelm in a constantly waterlogged state.

The acrotelm is able to reduce water losses even further during drought periods because when *Sphagnum* dries out it turns almost white. When the *Sphagnum* heads of the carpet surface dry out they therefore create an extensive white surface which reflects a significant amount of solar radiation away from the bog surface, thus reducing evaporative losses.

The other key function of the acrotelm is that it supplies material to the catotelm in the form of fresh peat. A bog cannot accumulate peat without a functioning acrotelm. Indeed without an acrotelm the accumulated peat of the catotelm is relatively defenceless and unable to prevent loss of this accumulated store of peat.

3.5.1.3 The nature and function of the catotelm

The catotelm represents the accumulated store of peat which has been slowly acquired from the acrotelm over several millennia. The nature of this peat varies with the changing nature of the vegetation assemblage which forms the acrotelm, and this assemblage changes in response to climatic shifts, some of which have been quite dramatic in the past 9,000 years. The peat remains only semi-decomposed because constant waterlogging means that normal aerobic decomposition cannot take place, but very slow anaerobic decomposition does occur within the peat with the result that the peat near the base of the bog has been subject to this low level of decomposition thousands of years and thus tends to be somewhat more decomposed than younger peat.

The catotelm is thus completely waterlogged and consists of diverse plant materials which are in various states of decomposition. It is important to understand that, being completely waterlogged, decomposition does not result in subsidence of the bog dome in the manner of a decomposing compost heap. The peat material is held in suspension within the overall mound of stored precipitation which is itself held in place, like a large droplet of water on a flat glass plate, by the extremely slow rate of water movement through the catotelm peat, which may be 1 million times slower than the speed of a snail. Indeed it is this very slow rate of water release which is the prime function of the catotelm because without this stored body of water the material passed down from the acrotelm would simply decompose. As it is, any material passing down from the acrotelm enters the waterlogged environment of the catotelm and joins the peat store – the store being the catotelm's other main function.

The water-retaining properties of living *Sphagnum* and *Sphagnum*-rich peat mean that in a natural raised bog the proportion of water to plant material by weight is often as high as 97% to 3%, while plant dry matter typically occupies only around 5% of the peat volume compared with water's 95% of the peat volume, although a substantial proportion of this water is contained *within* the plant material in storage cells. The proportional volume occupied by water *outside* the plant material is typically around 20% of the peat volume (Romanov, 1968; Ingram, 1983). This volumetric relationship becomes important when considering conditions in a residual peat layer.

3.5.1.4 The nature of the residual peat layer remaining on a cut-over bog

When industrial peat extraction ceases, the residual peat layer consists only of catotelm peat. It lacks the moderating functions of the acrotelm and thus experiences drying out of the catotelm peat which, now exposed to the atmosphere, begins to decompose aerobically. In addition, because water is now being lost from the peat matrix the volume of the drying peat changes, causing shrinkage and subsidence. The exposed peat is also very dark relative to a living, *Sphagnum*-rich bog surface and thus absorbs more solar radiation, warming the peat and causing further water loss through evaporation. Indeed it is this very process which is used to air-dry the loose peat when it is first milled.

The bare surface of the peat has no way of regulating water movement across its surface, but the peat matrix still makes it hard for water to seep down through the peat and so much precipitation input is lost through surface run-off and evaporation from the relatively warm surface. Replenishment of the drying surface by precipitation is thus not easy, with the result that, over time, the bare peat steadily loses both water (through seepage and evaporation) and peat material (through wind-blow, rain-driven erosion and through aerobic decomposition).

Given these various factors, it is sufficient to observe that the issues associated with leaving '...50 cm of strongly-humified peat...' are in fact much more complex than this apparently simple instruction suggests. Some of the hydro-chemical consequences have already been explored in the previous Sub-Question, but there are also a great many hydrological consequences which must be understood – some of them mutually antagonistic. Few of these lend themselves to any form of quantitative treatment in the manner of the hydro-chemical data in the previous Sub-Question. Consequently the review of hydrological issues will focus more on a narrative assessment of published information rather than any form of quantified synthesis.

3.5.2 Categorisation and assessment

Information relevant to this Sub-Question was examined in detail for 45 publications. Of these 44 publications, 22 were experimental studies, quantified field descriptions which provide measured values, field-based descriptions of hydrological behaviour relatable to peat depth or extensive reviews with much supporting field data and were thus categorised as 3+++. Two publications either review peat cracking and provide some evidence, or mention cracking as an incidental observation, and were thus classed as 3++ while two more gave typical values for, or specific consequences of, differing conductivities and were assigned a score of 3++. Twelve publications were reviews of hydrological behaviour including some field-based data or evidence and were classed as 2+++ while two publications were reviews which provided only cited values or thresholds and were classed as 2++. Two reviews provided useful information or valuable insights but gave no supporting evidence and were classed as 2+, while two further reviews provided only very basic threshold values with no supporting evidence and were classed as 1++ or 1+.

The sub-question can usefully be considered under five topic headings:

- Hydrological origins of the 0.5 m residual layer;
- Hydraulic conductivity of the residual layer;
- Other hydrological factors influencing the residual layer;
- Hydrological connections with the mineral sub-soil;
- Effect of residual peat layer on water-table behaviour.

3.5.2.1 Hydrological origins of the 0.5 m residual layer

The idea that 0.5 m of highly-humified peat is required for peatland restoration appears to have its origins in research undertaken in Germany and the Netherlands during the 1970s and 1980s. The earliest source of this research referred to by UK authors tends to be Eggelsmann (1980). The next source generally cited is a paper published by Blankenburg and Kuntze (1987). Schouwenaars (1993a) is then often cited as supporting these German research results and of refining the picture somewhat for peat which is not so strongly humified. Schouwenaars in fact published two relevant papers in 1993, one in German (Schouwenaars, 1993a) and one in English (Schouwenaars, 1993b). In these papers he draws on additional papers published by the range of earlier German researchers, most notably Eggelsmann and Klose (1982) and Eggelsmann (1987). Meanwhile Eggelsmann also published a further early and important paper concerning the topic (Eggelsmann, 1982).

Curiously, the earliest of these various cited papers (Eggelsmann, 1980) [2+++] has very little if anything to say about residual peat depths, being more about the characterisation and classification of water bodies (including bog pools). It does, however, include a diagram of a raised bog in which the indicated residual peat depth after planned peat extraction is 2-3 m.

Eggelsmann and Klose (1982) [3+++] present hydrological data for Lichtenmoor, a cut-over German raised bog subject to restoration management. They focus on hydrological aspects alone, explicitly noting that they do not consider chemical aspects of restoration in the paper. The site has a residual peat layer which varies between 80 cm and 200 cm over which a *Bunkerde* ('top-spit' of retained living layer) had been placed. Their results show that it is possible to re-establish a cover of *Sphagnum cuspidatum* but do not shed much light on the question of a 0.5 m residual thickness of peat. This is because the thickness at Lichtenmoor exceeds this residual peat depth in all places.

In their reviews of restoration conditions for cut-over raised bogs in Germany both Eggelsmann (1982) [1++] and Kuntze and Eggelsmann (1982) [1+] refer to a 0.5 m residual thickness, although both explicitly present this only as a means of providing an adequate water balance by minimising seepage losses into the underlying mineral ground. Eggelsmann (1982) adds certain other provisos, specifically recommending that [translated from the original German]:

- no ditch should cut into the sub-soil;
- the black (humified) peat layer should everywhere have a minimum thickness of 0.5 m, and a bigger thickness is advantageous;
- there should ideally be a 'Bunkerde' layer spread to a thickness of 0.2-0.3 m, a bare milled surface being – according to the current state of knowledge – not an ideal surface [for restoration].

Eggelsmann (1987) [2+++] provides an in-depth review of 'ecotechnical' lessons learned in the restoration of cut-over raised bogs. He makes no explicit comment about residual peat depth, but illustrates two conditions – one in which a ditch remains within the peat layer and one in which a ditch cuts through the peat layer into the mineral subsoil. In the first of these the residual peat depth is illustrated as some 130 cm thick, while in the second case the residual peat layer is explicitly indicated as *greater* than 50 m thick, plus it has a further 30 cm layer of 'top spit' on top of this. Eggelsmann (1987) also notes that if the objective is to have bog hollows form, a minimum residual thickness of 1.2 m is required, while if open-water bog pools are to form then the residual peat depth requires a minimum of 2.0 m, and he emphasises the importance of such features in contributing to the distinctive and characteristic biodiversity of the bog habitat.

Blankenburg and Kuntze (1987) [2+++] present calculations based on a hydrological model derived from a set of representative data. According to the hydrological model, increasing residual peat depth to more than 0.5 m achieves little in terms of reducing downward seepage, but if the residual peat is not strongly humified (at least H7), this thickness will not retain sufficient water within the peatland. They emphasise that highly humified peat can crack if it dries out, so the residual peat thickness of peat humified to at least H7 must not be less than 0.5 m. Furthermore, they state that, in order to prevent drying out, such peat must be covered by a thickness of *Bunkerde* which is at least 0.3 m thick.

Schouwenaars (1993a) [2+++] cites some of these earlier research studies and offers further evidence from the Netherlands. He also highlights a number of key factors. In particular, Schouwenaars (1993a) highlights the fact that the figures given by Blankenburg and Kuntz (1987) for a layer of strongly humified residual peat layer also assumes that, *in addition*, a *Bunkerde* layer of at least 30 cm layer must sit on top of this humified layer. He also highlights that that the residual peat layer should not be less than 0.5 m because there is a risk of the peat cracking. He emphasises that peat of H7 or more is necessary to limit water losses to acceptable levels through downward seepage if the strongly humified layer is 0.5 m thick. Where the peat is less humified, Schouwenaars (1993a) notes that downward seepage rates are 2 to 3 times greater. Where the mineral sub-soil is clay or loam a residual peat thickness *of 0.5 – 1.0 m "is often sufficient"*, but if there is no supply from the underlying groundwater table then a residual peat depth of at least 1.0 m is necessary.

Two points in particular are worth noting in the light of these statements from these various authors. Firstly, they are quite clear that the layer of strongly humified peat should not be *less* than 0.5 m. Secondly, there is recognition that such a layer is in danger of cracking if it dries out and thus it must be covered with a 'top-spit' layer which is at least 30 cm thick. Thirdly, the figures presented by these various authors are concerned only with hydrological considerations, not whether the *quality* of water supply, for example, is suitable for restoration to *bog* conditions. In fact the reliance placed by Schouwenaars (1993a) on groundwater pressure and supply from the underlying mineral sub-soil makes it clear that restoration explicitly to bog is not a major consideration. The focus is instead rather on restoration and maintenance of peat-forming conditions.

These various key points place a somewhat different complexion upon the publications of Eggelsmann, Blankenburg, Kuntz and Schouwenaars and the interpretation placed on their research by various UK publications and documents which have since used translations of these papers – or parts of these papers – as the basis for decisions about residual peat depths and bog restoration. In the light of this somewhat altered perspective and the key points raised, a substantial body of published research is available and relevant, covering a number of topics and with much to offer concerning the question of whether a layer of 0.5 m of strongly-humified peat offers a suitable surface on which to restore ombrotrophic bog. It is worth beginning a review of this research with the question of downward seepage losses, which are almost the sole focus of the German and Dutch publications currently used in the UK to justify a residual peat depth of 0.5 m.

3.5.2.2 Hydraulic conductivity of the residual layer (potential water transmission rates)

Ingram (1983) [2+++] in his review of peatland hydrology observes that measurements of hydraulic conductivity (k) for the deepest parts of a bog are rare, but notes that average values for catotelm peat are around 10^{-4} cm s^{-1} = 0.86 m d^{-1}. Baird *et al.* (2008) [3+++] give values of 'k' for differing depths within the catotelm of Cors Fochno raised bog, near Aberystwyth, noting that values range between 10^{-4} cm s^{-1} and 10^{-5} cm s^{-1}, with a marked shift towards 10^{-5} cm s^{-1} at a depth of 4 m which probably represents the start of the basal 'fibrous/forest' peat layers noted by Williams Parry and Parker (1939) and Moore (1963) both illustrated by Slater (1972) [3+++].

Ryecroft *et al.* (1975) [2+++] highlight the fact that hydraulic conductivity is affected significantly by degree of humification. They critically examine and re-work laboratory data obtained by Malmström (1925) and so derive a set of values relating humification to hydraulic conductivity (see Table 6).

Table 6. Values for horizontal and vertical hydraulic conductivity of peats at various degrees of humification, calculated by Ryecroft et al. (1975) from laboratory data obtained by Malmström (1925). Reproduced with kind permission of British Ecological Society and Wiley.

		Hydraulic conductivity (cm sec^{-1})	
Peat type	Humification*	Horizontal	Vertical
Carex-Sphagnum	2	$8.0 \times 10^{-}3$	-
Trichophorum cespitosum-Sphagnum	2	1.6×10^{-3}	8.5×10^{-3}
Sphagnum fuscum	3	3.6×10^{-3}	1.7×10^{-2}
S. fuscum	4-5	7.3×10^{-4}	2.2×10^{-3}
S. fuscum	6	2.9×10^{-4}	1.6×10^{-4}
S. fuscum	7	1.7×10^{-4}	1.7×10^{-4}
Dy (gel-mud) peat	8-9	4.4×10^{-5}	3.8×10^{-5}
Dy (gel mud) peat	9	4.6×10^{-6}	1.0×10^{-5}

*Scale according to von Post and Granlund (1926)

Clymo (1983) [2+++] presents humification data for a profile of Ramna Bog, Sweden, in which it is evident that while the degree of humification increases steadily with depth, they begin to oscillate wildly towards the base of the peat column, ranging from H5 to H10 in only 10-20 cm vertical distances down the column. Wheeler and Shaw (1995) [2++] similarly illustrate the distribution of humification in a cross-section of Raheenmore Bog, Ireland, and here again the basal sediments range from H5 to H7. Smolders *et al.* (2003) [3+++] also note the high variability of humification within catotelm peat. It is therefore worth noting that the values given in Table 5 for H4-5 show a higher conductivity in the vertical direction than in the horizontal direction, with a vertical rate of 2.2×10^{-3} cm sec^{-1} compared with a horizontal rate of 7.3×10^{-4} cm sec^{-1}. Conductivity at H5 is an order of magnitude greater than that for H7, which is given as 1.7×10^{-4} cm sec^{-1}. The rate of vertical conductivity for H5 thus equates to 1.9 m per day. Though actual seepage loss ('transmissivity') would be a product of both hydraulic conductivity and layer thickness and would be substantially less than rates calculated purely based on hydraulic conductivity, such rates are nevertheless unlikely to be the kinds of values envisaged by Eggelsmann and other early German researchers when recommending a residual peat thickness of 0.5 m.

Baird *et al.* (in press) [3+++] have provided clear confirmation that variable hydraulic conductivities developed in the acrotelm, while peat is being laid down can persist through the whole peat column, resulting in highly variable values for hydraulic conductivity even within the deepest parts of the catotelm. They emphasise the need to re-think the widely-held assumption that catotelm peat is largely uniform in its properties and recognise that it can vary substantially over horizontal distances of only 1-2 metres.

Meanwhile Joosten (1995) [2+] notes that when the main bulk of the catotelm is removed this reduces total hydraulic resistance down through the profile to an extent which is not fully compensated for by the reduction in hydraulic head, potentially causing increased seepage through the residual layer.

3.5.2.3 Other hydrological factors influencing the residual layer

Values for hydraulic conductivity give some measure of potential water transmission rates but these values assume that the catotelm peat is uniform in nature. This is unlikely to be the case, given the evidence discussed immediately above. It is also unlikely precisely because the peat is only 0.5 m thick and (if the general recommendation is followed) it consists of strongly-humified peat. Morgan-Jones *et al.* (2005) [3+++] point out that assumptions about low discharge (water loss) through the catotelm can only be assumed to apply when the lower part of the catotelm forms part of a fully-functioning raised bog. They state that when the catotelm is no longer part of such a system these assumptions no longer apply because the catotelm peat can become 'highly anisotropic' (i.e. extremely variable in structure and character) and has a tendency to form cracks.

Cracking is a by-product of a more fundamental hydrological process, which is shrinkage as a result of drying. Indeed there is an intrinsic internal conflict within the original German recommendation that a 0.5 m layer of strongly-humified residual peat should remain to provide a hydrologically secure base on which to restore bog habitat. Hobbs (1986) [3+++], in his extensive review of the engineering properties of peat, describes the processes which result when water is lost from the peat matrix. These processes are essentially subsidence and shrinkage. Graham and Hicks (1980) [3+++] demonstrate that the more humified the peat the more dramatically it will shrink when dried. Perhaps surprisingly, the most dramatic volume changes take place in the drying stages which occur while the peat is still in the ground and subject to the drainage regime required for peat milling (i.e. during drainage from 95% to 80% water content). Consequently this dramatic shrinkage, which can result in volume changes of up to 60% in strongly humified peat, will tend to reduce the planned residual thickness and continue to do so until the drainage system of the milling fields can be sealed up.

By specifying that the peat should be strongly humified, this recommendation also makes it more likely that the residual peat layer will undergo significant cracking during the final phases of commercial operations. That cracking tends to occur with drying is a widely recognised phenomenon. As already highlighted, Schouwenaars (1993a) [2+++] specifically highlights the need to have at least 0.5 m of strongly humified residual peat in order to reduce the effects of cracking. Several authors mention the presence of cracks in residual layers of peat or even within the lower parts of uncut raised bog systems. When water is lost through drainage and evaporation because the acrotelm has been removed, the potential 60% change in its volume through loss of water and oxidative losses of the peat matrix itself cannot be accommodated wholly by vertical subsidence. Consequently the matrix shrinks laterally as well. It is impossible for the matrix to shrink as a single vast body and therefore, as with a drying layer of mud, cracks form in the peat to produce the required change in volume. A particularly dramatic example of such cracking is illustrated by Blankenburg (2004) [2+++], but many cracks are not so immediately visible. Cracking such as that illustrated by Blankenburg has also been recorded by Pyatt *et al.* (1987) [3++] and Lindsay and Bragg (2004) [3+++] beneath conifer forests planted on peat, but these authors also illustrate the way in which deep cracks tend to form along the beds of drains. Kleimeier *et al.* (2014) [3++] also observed cracks in artificially drained peat and these cracks extended through the thin peat profile into the gyttia beneath the peat. Perhaps rather surprisingly, cracks have also been found in the basal layers of natural raised bogs. Hughes (2000) [3+++] has identified a dry successional sequence for some UK raised bogs in their transition from fen to bog ('the FTB transition') during which they were dominated by a dry vegetation and the surface peat experienced cracking, which is then preserved within these basal layers.

Furthermore it is not even necessary for the peat to crack to provide preferential routes for water to pass through the residual layer of peat. Sliva and Pfadenhauer (1999) [3+++] found that the basal layer of peat permitted transmission of water between the peat surface and the underlying mineral ground because in places the basal peat consisted of relatively long and fibrous *Eriophorum vaginatum* remains which did not create an amorphous (and thus low-permeability) matrix but instead provided routes for preferential water movement. As Hughes and Barber (2003) [3+++] and Hughes and Barber (2004) [3+++] amongst many others show, it is very common for UK raised bogs to have a layer of *Eriophorum vaginatum* peat at the interface between fen peat and *Sphagnum*-rich bog peat. The evidence from Baird *et al.* (in press) referred to earlier lends further weight to the argument that preferential routes for water transmission are likely to exist within a residual peat layer.

3.5.2.4 Significance of hydrological connection with the mineral sub-soil

Wheeler and Shaw (1995) [2++] state that water losses from the residual peat thickness to the mineral sub-soil may not be important where the site overlies an impermeable sub-soil but could have "profound repercussions" in other circumstances. They therefore recommend a careful examination of hydrological conditions where there may be concerns about sub-peat soils. In terms of maintaining a *hydrological balance* which is suitable for ombrotrophic conditions if only a relatively thin layer of residual peat remains, the permeability of the mineral sub-soil is certainly a feature requiring careful examination. Wheeler and Shaw (1995) state that 'many UK sites' overlay impermeable mineral ground, but Morgan-Jones *et al.* (2005) [3+++] examine the hydrological properties of 'Hydrological Protection Zones' (HPZ) – which represents the ground which must be hydrologically managed around a remnant raised bog in order to maintain optimal hydrological conditions within the remnant. They give examples of HPZ consisting of different soil profiles. One of these is 0.5 m of peat overlying 1.5 m of clay, and they conclude that as long as the HPZ is largely underlain by this thickness of clay, they predict that "*significant drawdown only occurs in the top 0.5 m*." In the case of a soil profile with 0.5 m of peat, 0.5 m of clay and 1 m of sand, they predict a possible drawdown of up to 2 m.

Furthermore it is not so clear that 'many UK sites' are underlain by wholly impermeable deposits. Morgan-Jones *et al.* (2005), for example, give details of underlying deposits for a number of UK lowland raised bogs and frequently note the presence of sands and gravels. Roger Meade Associates/Maslen Environmental (2008) [3++] demonstrate the need to allow for varying the extent of an HPZ in differing parts of a UK raised bog site precisely in order to take into account varying porosity of the underlying mineral soils and varying hydraulic properties of the peat itself. Joosten (1995) [2++] observes that where the mineral sub-soil has high transmissivity, lowered groundwater water tables up to several kilometres from the restoration site can increase downward seepage.

Most of the remaining raised bogs in Britain are now found in Scotland and NW England. Some of these lie on alluvial plains which can have highly complex sub-surface deposits as a result of river-meander dynamics, while the British Geological Survey's 'Superficial Engineering Geology' map, available via the Engineering Geology Viewer, reveals that a large proportion of remaining UK raised bog sites now overlie deposits of glacial till. The characteristics of glacial till can be highly variable because it consists of material which has been abraded from whatever landscape the glacier has passed over. Stephenson *et al.* (1988) [3++] provide hydraulic conductivity values for differing geologies and illustrate the fact that conductivity of the most porous glacial till can reach 1.2×10^{-3} cm sec^{-1}, which is an order of magnitude faster than the value for H7 peat given above in Table 6.

In addition to providing possible routes for water to be lost from the site through cracks, more transmissive peat and more porous mineral sub-soils, these various features also have the potential to operate in reverse fashion during periods of heavy or prolonged rain. Once the cracks and porous sub-soil deposits have filled with precipitation inputs, minerotrophic water can well up and spill out from cracks and other hydrological connections to the mineral base and inundate the immediate area with minerotrophic water. Sliva and Pfadenhauer (1999) observed this phenomenon regularly on their restoration site and many researchers have highlighted the essentially minerotrophic nature of the surface waters on their restoration sites (as explored in Sub-Question 2 above). Thus, while the focus of the original German recommendation for 0.5 m residual peat layer was directed to achieving an adequate hydrological budget, there are also hydro-chemical consequences from having such a thin residual layer.

It is presumably because of concerns about both water loss and possible chemical enrichment which cause Eggelsmann (1982) to state that no drain must cut into the mineral sub-soil. Given this clear statement, it is also relevant to take into account the fact that, as noted above, drain bases are one locality where cracks are likely to develop. Consequently while the engineered drain profile may not cut into the mineral sub-soil, any cracking will deepen the drain and increase the possibility that the drain will, in effect, reach the mineral sub-soil. Wheeler and Shaw (1995) likewise observe that decisions about the depth of residual peat "*must take into account*" the depth of peat beneath the bases of all drains, presumably reflecting Eggelsmann's concerns.

3.5.2.5 Hydrological effects of the residual peat layer on water-table behaviour

As described earlier, the residual peat layer is a remnant layer of catotelm peat with no acrotelm to act as a moderating hydrological influence. Furthermore, this catotelm peat is now exposed to aerobic decomposition and is also subject to shrinkage and compression as water is lost from the peat. It is worth highlighting that shrinkage due to water loss affects the entire peat column, not merely the surface layer of peat which has been drained. Eggelsmann (1975) [2+++] demonstrates the effect on each section of the peat column, while Anderson *et al.* (2000) [3+++] provide more recent field data which corroborate this process. It can thus be assumed that the effects of drainage on the hydrological behaviour of the peat are felt throughout the whole thickness of the residual peat layer.

Considering the natural condition initially, values presented by Ingram (1983) [2+++] for a reasonably undisturbed bog in Scotland (Dun Moss, Perth and Kinross), these reveal that the water-table resides within 5 cm of the bog surface for much of the time and falls to a maximum of -26 cm. Lindsay (2010) [2+++] presents similar data for the central part of Cors Caron raised bog, Ceredigion. These figures can then be compared with water-table data obtained from cut-over sites. McCarter and Price (2013) [3+++] provide data to show that an un-restored area of milled peat with 1.7 m of residual peat has an average water table of -42.3 cm with a total range of around 55 cm. At times the water table falls to almost -80 cm. In contrast, a restored area of the same site has a mean water table of -27.3 cm but with a total range of around 95 cm, on occasion still falling as low as the lowest values for the un-restored area. Poulin *et al.* (2005) [3+++] provide water-table data for 105 baulks and 96 trenches from un-restored block-cut sites and for 34 un-restored milled sites which show that the average water table of the trenches was -56 cm, while in the baulks it was -96 cm and in the milled fields it was -82 cm. Over a period of just less than three years, Money (1995) [3++] observed an average water table of approximately -40 cm for a commercially cut-over area of Thorne Moors, Humberside, but recorded lowest water levels of approximately -95 cm. Girard *et al.* (2002) [3+++] record water levels from 26 trenches in an abandoned block-cut site (Cacouna Bog, Quebec) which has undergone a degree of spontaneous revegetation. The residual peat depths vary between 1.39 m and 3.89 m. The average water table across the 26 trenches was -46.3 cm with an averaged range of 11.2 cm, but in some trenches the water table was as low as -70 cm with a 7-9 cm range. Konvalinkova and Prach (2014) [3+++] recorded water tables for 11 milled sites in the Czech Republic. Their data indicate an average water table of approximately -45 cm across the 11 sites, but the deepest levels for a high proportion of sites exceeds -70 cm.

Price *et al.* (1998) [3+++], meanwhile, recorded water tables in a block-cut bog where the drains had been blocked and found that the water table on a relatively flat area of the site still fell to -70 cm at times. Karofeld *et al.* (2015) [3+++] on the other hand, found that two areas of restored milled peat – one restored to a 'high water table', the other to a 'low water table' – had average water levels of -23.5 cm and -30.4 cm respectively. The wet-restoration area fluctuated between -11 cm and -41 cm while the dry restoration sector fluctuated between -18 cm and -44 cm.

It is evident that such water-table behaviour is of considerable significance if the residual peat layer is 0.5 m thick, as many of these fluctuations take the water table to the bottom of this layer or even beyond. In an in-depth review of peatland hydrology as it is affected by commercial peat operations, Price *et al.* (2003) [2+++] provide a detailed exploration of the factors which give rise to the water-table behaviour of these industrially-worked sites, and they highlight that unexpected consequences arise from following the concept of retaining a 0.5 m thickness of strongly-humified peat as the residual layer.

In the undrained state, highly humified peat consists of many small peat particles suspended in a comparatively large volume of water because these small particles have only a small storage capacity within each particle. This is because decomposition has broken open many of the hyaline cells of *Sphagnum* which normally provide a large volume of internal storage. In addition, the stems and branch spindles of the living *Sphagnum* plant are by now broken into very small fragments, whereas in peat of low humification there are many such lengths of stem and branch spindle which act as a 'scaffolding' which prevents the *Sphagnum* fragments from compressing closely together (see Figure 5). This scaffolding maintains large pore spaces between fragments which means that it only requires a small fall in the water table to release large volumes of water into drainage or the atmosphere through evaporation. In contrast, when the particles in the peat matrix are very small and possess little internal storage capacity, removal of water through drainage and evaporation causes these particles to collapse together, causing the peat to shrink and creating very narrow spaces between the particles.

Price *et al.* (2003) observe that these changes also therefore bring about substantial changes to the 'specific yield' of the peat – specific yield being the amount of water which can be drained from the peat through gravity alone. Price *et al.* (2003) note that simply removing the acrotelm from a bog can reduce the specific yield from around 0.6 (provided by the acrotelm) to 0.2 (characteristic of catotelm peat). The processes of compression and oxidative decomposition have then been shown to reduce specific yield within only 5 years to somewhere between 0.04 and 0.06 – i.e. an almost 10-fold decline in the catotelm peat and a more than 10-fold decline from the natural state.

Figure 5. Close-up of Sphagnum stems and branch spindles mixed with Sphagnum leaves in peat with a low state of humification (H4 on the von Post scale). These stems and branch spindles prevent the particles from collapsing together, maintaining an open structure even though the supporting medium of water has now been removed. © Richard Lindsay

For a given volume of water, water must fall a much greater distance within the many small channels between the particles of this more decomposed compressed peat than was the case when a more open, water-filled structure existed, while the narrowness of many channels means that less water is readily given up in the form of specific yield. Price *et al.* (2003) observe that this reduction in specific yield results in greater water-table fluctuation, a reduction in the time that the water table approaches the peat surface, and a substantial fall in pore-water pressure. This last is important because Hayward and Clymo (1982) demonstrate that if pore-water pressure falls below -100 mb this will cause the hyaline storage cells of Sphagnum to release their internally-stored water and will prevent further water uptake by the plant. Equally, Schouwenaars (1993b) [3+++] provides data which indicate that a water-table depth of around 17 cm is critical because this is the depth below which capillarity can no longer supply all water needs to the living capitula of *Sphagnum*. Price *et al.* (2003) thus note that the combination of reduced specific yield and reduced pore-water pressure will tend to cause *Sphagnum* on the surface of the peat to desiccate – or prevent its successful colonisation.

Gorham and Rochefort (2003) [2+] and Quinty and Rochefort (2003) [2++] review a range of factors influencing peatland restoration after commercial peat extraction and, in the light of the information presented by Price *et al.* (2003), advocate three threshold conditions for the successful re-establishment of *Sphagnum*. They set these thresholds as:

- a water table of -29 cm with a range of 28 cm;
- 50% soil moisture; and
- a soil-water pressure of -100 cm for the whole year.

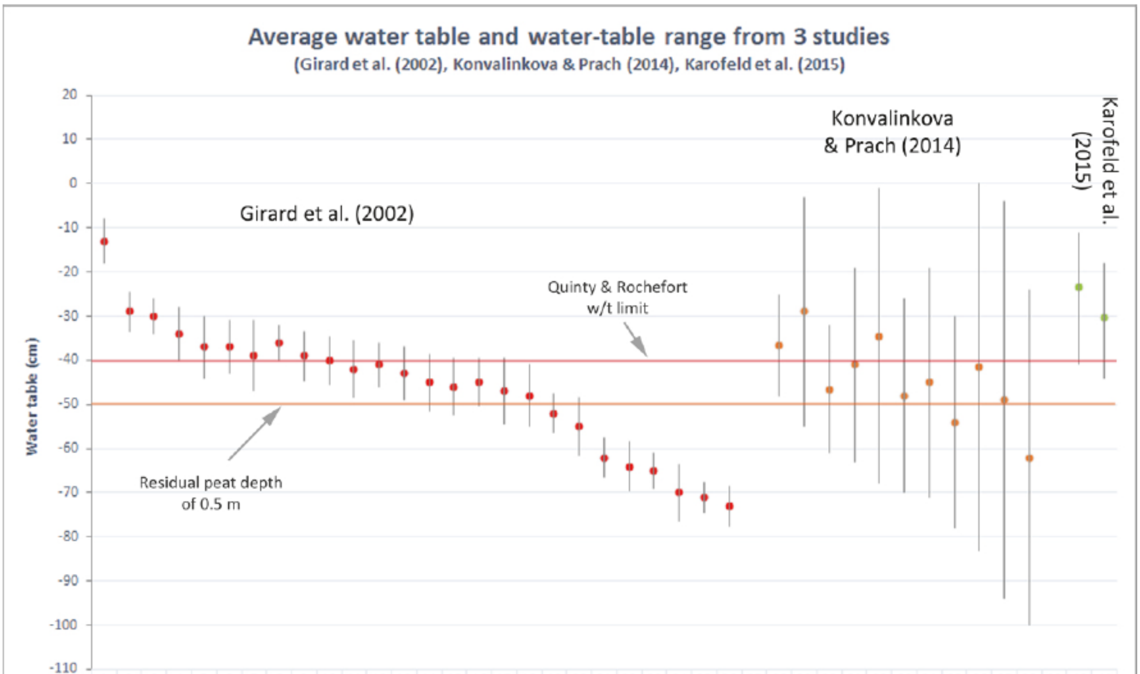
They do not specify, however, whether this is for aquatic or terrestrial *Sphagnum* and so make no distinction between development of 'poor-fen' *Sphagnum cuspidatum/fallax* carpets or ombrotrophic bog species such as *S. capillifolium*.

3.5.3 Synthesis

It is possible to draw together in a consistent manner at least some of the hydrological data presented within the publications discussed above. Specifically, the water-table range and the mean can be collated from Girard *et al.* (2002), Konvalinkova and Prach (2014) and Karofeld *et al.* (2015) – see Figure 6. The values of Girard *et al.* (2002) were obtained from trenches within a block-cut peatland, while those of Konvalinkova and Prach (2014) and Karofeld *et al.* (2015) are from milled surfaces. The differences in water table behaviour between that of block-cut trenches and milled fields is quite striking. Furthermore, the values for Karofeld *et al.* (2015) are derived from a site which is currently undergoing restoration management in the form of a re-established *Sphagnum* sward, whereas some of the sites measured by Konvalinkova and Prach (2014) were not at the time subject to any restoration management.

Also indicated on Figure 6 is the 0.5 m residual peat thickness which the present review is considering, from which it can be seen that most of the milled sites studied by Konvalinkova and Prach (2014) experience water levels which would fall below the base of the residual peat layer and into the mineral sub-soil. This is also true of some trenches studies by Girard *et al.* (2002), whereas the water table in the restoration site studied by Karofeld *et al.* (2015), which has a residual peat thickness of 2.5 m, never falls as deep as -50 cm into the peat.

Furthermore Figure 6 also displays the -40 cm water table threshold below which Gorham and Rochefort (2003) and Quinty and Rochefort (2003) say the water table should not fall if the site is to undergo successful restoration management. A large proportion of the mean values obtained by Girard *et al.* (2002) can be seen to fall below this threshold, while most of the mean values obtained by Konvalinkova and Prach fall below this threshold. The two mean values for the restoration site studied by Karofeld *et al.* (2015), on the other hand, lie well above this threshold.



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
Min	-8	-25	-26	-28	-30	-31	-31	-32	-34	-35	-36	-36	-37	-39	-40	-40	-40	-41	-48	-49	-58
Max	-18	-34	-34	-40	-44	-43	-47	-40	-45	-46	-49	-46	-49	-52	-53	-51	-55	-55	-57	-62	-67
Mean	-13	-29	-30	-34	-37	-37	-39	-36	-39	-40	-42	-41	-43	-45	-46	-45	-47	-48	-52	-55	-62

	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41
Min	-59	-61	-64	-68	-69		-48	-55	-61	-63	-68	-70	-71	-78	-83	-94	-10		-11	-18
Max	-70	-69	-77	-75	-78		-25	-3	-32	-19	-1	-26	-19	-30	0	-4	-24		-41	-44
Mean	-64	-65	-70	-71	-73		-37	-29	-47	-41	-35	-48	-45	-54	-42	-49	-62		-24	-30

Figure 6. Average water tables and water-table ranges obtained from three studies of cut-over peatlands. The red dots represent the mean water-table values obtained from Girard et al. (2002) from trenches in a block-cut bog, the orange dots represent the mean water-table values calculated from Konvalinkova and Prach (2014) from abandoned milled surfaces and the green dots represent the mean water-table values provided by Karofeld et al. (2015) for a milled surface undergoing restoration. The vertical line associated with each dot represents the water-table range. Values used are provided in the table beneath the graph. Also indicated is a red horizontal line which represents the -40 cm threshold recommended by Quinty and Rochefort (2003) for the lowest water table advisable when attempting to re-establish Sphagnum, and an orange horizontal line which represents a 0.5 residual thickness of peat. If the water table falls below this, it enters the mineral sub-soil.

It is also possible to compare mean residual peat depth with mean water tables for Konvalinkova and Prach (2014) and Karofeld *et al.* (2015). Unfortunately Konvalinkova and Prach (2014) give peat-depth ranges for most of their sites, and the consistent maximum of 100 cm suggests that their measuring device was only 1 m long. The actual maximum peat depth in their ranges may therefore be more than 100 cm but it is only possible to work with the data provided. The mean residual peat depths were calculated from the ranges given by Konvalinkova and Prach (2014), nevertheless acknowledging that the actual maximum peat depth may be greater than indicated by those authors. The results can be seen in Figure 7, which also indicates the threshold for water table depth recommended by Quinty and Rochefort (2003) as well as indicating the -50 cm depth which would represent the base of a 0.5 m residual peat layer. From this it can be seen that the mean water table is likely to be held reliably above the Quinty and Rochefort (2003) threshold of -40 cm only if the residual peat depth is more than 100 cm thick. Anything less than this is likely to see the mean water table sits virtually at the base of the residual peat layer, representing a challenge for *any* form of peatland restoration, whether fen or bog.

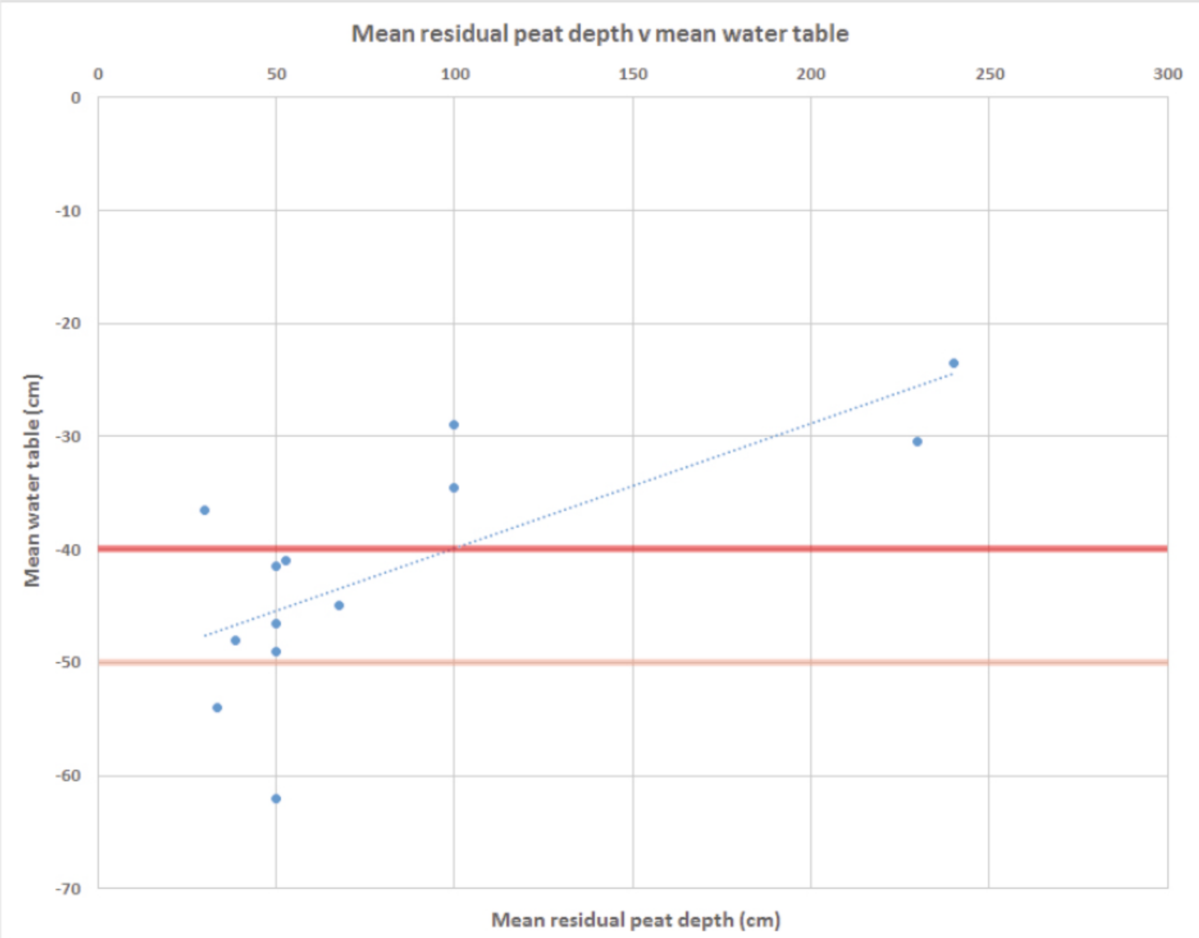


Figure 7. Mean water tables obtained from Konvalinkova and Prach (2014) and Karofeld et al. (2015) plotted against mean residual peat depth. A linear trend line has been added as a blue dashed line. Also indicated is a red horizontal line which represents the -40 cm threshold recommended by Quinty and Rochefort (2003) for the lowest water table advisable when attempting to re-establish Sphagnum, and an orange horizontal line which represents a 0.5 residual thickness of peat. If the water table falls below this, it enters the mineral sub-soil.

On the basis of the information reviewed and considered above, there is **strong** stratigraphic evidence to show that a raised bog cannot be assumed to have a strongly humified layer of peat forming the bottom-most 0.5 m of the bog.

There is **strong** hydrological evidence to indicate that the peat at the base of a raised bog sometimes permits relatively high levels of downward seepage to the mineral sub-soil.

There is **strong** hydro-physical evidence to indicate that strongly-humified peat shrinks and cracks when it dries, providing routes for direct water transmission to and from the mineral sub-soil, particularly when the residual peat layer is thin.

There is **strong** stratigraphic and geological evidence to indicate that the mineral sub-soils beneath UK raised bogs sometimes consists of materials which are known to allow relatively high rates of water movement from or into the basal peat layer.

There is **strong** hydrological evidence to show that water tables in cut-over raised bogs tend to be lower, and display greater fluctuations, even when subject to restoration management, than water tables in undisturbed raised bogs.

There is **strong** hydrological evidence to suggest that a milled site with a thick residual layer of peat will support a relatively high mean water table and restrict water-table fluctuations within a zone no deeper than -40 cm, whereas a site with a thin residual peat layer will support a lower mean high water table and the water table fluctuations will be greater, extending below -40 cm and in some cases extending more than -50 cm below the surface.

There is **weak** hydrological evidence to support the recommendation that 0.5 m of strongly-humified residual peat alone is a suitable base upon which to achieve hydrological conditions which mirror an ombrotrophic raised bog.

3.6 Sub-Question 4: Does residual peat depth influence the vegetation achieved during bog restoration?

3.6.1 Background

Ultimately, although it is possible to define a possible set of chemical and hydrological parameters which may indicate that ombrotrophic bog is developing on a restoration site, the key indicator is invariably going to be the vegetation because (a) it is the most readily measured feature, (b) the vegetation is a good biological indicator of factors which are sometimes hard to measure or may even be unknown, and (c) it is the vegetation which creates a bog. Earlier in the present review the question of what actually defines a 'bog' was considered particularly in relation to water source and nutrient supply. Økland *et al.* (2001) were cited as arguing that within a given region it is possible to identify regional indicators of ombrotrophic conditions. This is a critically important point because it is possible more easily to claim that a target has been successfully achieved if the target is made rather generic instead of locally specific.

There is, for example, much published literature, both within peer-reviewed journals and in material produced by a number of sectoral interests, which talks of '*Sphagnum*' colonisation, presence, absence or introduction, without ever making clear which species of *Sphagnum* are being considered. Indeed sometimes the literature combines all bryophytes (mosses and liverworts) together and talks of the response of the 'bryophyte' component. This is rarely a helpful approach as different species of moss and liverwort have very different responses to given sets of conditions.

So, when approaching the question of the way in which residual peat depth influences vegetation it is important to be clear that the primary focus, in terms of meeting a planning condition requiring restoration to bog, is the assemblage of species which in the UK are recognised as being characteristic of ombrotrophic bog conditions – and given that planning consents for industrial peat extraction are almost entirely concerned with lowland raised bogs, the vegetation assemblage can be narrowed down to species characteristic of that habitat. A number of accounts, datasets and analyses have described the lowland raised bog habitat as a distinct component of the UK assemblage of habitats during the past few decades, most notably Tansley (1939), Goode and Ratcliffe (1977), Daniels (1978), Rieley and Page (1990) and Rodwell (1991a,b; 1995). While Tansley (1939) defines ombrotrophic raised mires and minerotrophic valley mires as 'bogs' because he uses a chemical signature to define 'bog' habitat, Daniels (1978) identifies his types according to vegetation composition and arrives at a set of vegetation types which in some cases combine raised bog and blanket bog, while in others raised mires and valley mires are combined. A few vegetation types are assigned solely to raised mires. Rodwell (1991b) made use of a much wider set of field data, including that of Daniels (1978), and identified one vegetation type which he assigned to both raised and blanket mire (M18 *Erica tetralix-Sphagnum papillosum* raised and blanket mire), together with two communities which occur on raised and blanket mire but which also occur in poor fens (namely M2 *Sphagnum cuspidatum/recurvum* bog pool community and M3 *Eriophorum angustifolium* bog pool community).

Wheeler *et al.* (2003) subsequently make use of a vegetation assemblage which they term 'RPM' based on a combination of *Sphagnum rubellum* [=capillifolium], *S. papillosum* and *S. magellanicum* to argue that this assemblage is typical of undisturbed raised bog systems characterised by Rodwell's M18 community but is described as equally characteristic of certain minerotrophic fen systems. They cite the example of a minerotrophic system at Bramshaw Wood which is described as having this RPM vegetation. A species list is provided for the site, containing species such as *Juncus bulbosus* and *Sphagnum auriculatum var. auriculatum*, plus *Molinia caerulea* and *Sphagnum palustre*. The first two species alone indicate a clear minerotrophic influence and do not appear in the species table for Rodwell's M18 bog vegetation community (Rodwell, 1991b) which Wheeler *et al.* (2003) cite, while *Sphagnum palustre* is found only on the slightly flushed margins and in the lagg fen of raised bogs in Britain. Over-simplistic use of a concept such as 'RPM' thus blurs the distinction between two site types which Du Rietz (1954) and Økland *et al.* (2001) would argue are quite distinct.

One effect of blurring the distinction between bog and fen is that it can lead to unjustified claims of successful 'bog' restoration when in fact the system is still *functionally* a minerotrophic fen with some groundwater influence. Restoration to 'bog' cannot be said to have occurred until such time as this minerotrophic phase is replaced by truly ombrotrophic bog conditions, as indicated by the absence of species which are local or regional indicators of minerotrophic conditions. It is, however, important to bear in mind that restoration research from countries other than Britain will have local vegetation indicators of raised bog which may differ from those in Britain. Thus, for example, raised bogs in the west of Ireland tend to support species such as *Molinia caerulea* and *Pleurozia purpurea* as components of natural bog vegetation (JNCC SAC website), although both would look out of place on a British raised bog. Similarly, as mentioned earlier, Finnish peatland specialists find it curious that Britain's main raised bog vegetation community (M18) should be characterised by *Sphagnum papillosum*, which is regarded as a fen species in Finland, but equally, some raised bogs in Finland have a natural, if slightly stunted, forest of pine (*Pinus sylvestris*) across the mire expanse (Ruuhijärvi, 1983) whereas in Britain pine is generally an invasive species of drying raised bogs. Meanwhile in Canada there are several exclusively North American species, although most of the Sphagna are the same.

Care must therefore be taken when considering literature describing the relationship between residual peat thickness, restoration actions, species composition and indications of success in terms of ombrotrophic bog establishment.

3.6.2 Categorisation and assessment

Information relevant to this Sub-Question was examined in detail for 34 publications. Of these 34 publications, 18 were experimental studies or quantified field descriptions which provide detailed vegetation information relatable to peat depth, and were thus categorised as 3+++. Eight publications gave useful information about the vegetation of peat bog sites but did not relate this to depth of peat and so were classed as 3++. Two publications gave indications of vegetation from survey work rather than detailed vegetation descriptions, and did not link these indications to specific peat depths. These were classed as 3+. Two publications provided a review of the relationship between species responses and peat depth and provided useful field data but no explicit link between vegetation and residual depth of peat and were thus classed as 2+++. Two publications provided information about broad vegetation types after restoration at a number of sites but with no clear link to peat depths and were thus classed as 2++. Two publications were classed as 2+ because one gave an incidental description of fen vegetation at a particular restoration site while the other provided a review which specified thresholds for depth and target vegetation types.

This sub-question can be addressed from the perspective of four topic areas:

- Required minimum peat depth in the natural system;
- Individual site studies of spontaneous re-vegetation;
- Multiple-site studies of spontaneous re-vegetation;
- Restoration studies involving active species transplants.

3.6.2.1 Required minimum peat depth in the natural system

Considering first the natural ombrotrophic system, Paradis *et al.* (2015) [3+++] investigate the margins of 20 raised bogs in New Brunswick, Canada, gathering data for both peat depth and vegetation composition along transects running from the bog into the lagg fen. The transition from bog vegetation to fen vegetation is identified using a split moving-window dissimilarity analysis (SMWDA) and the corresponding peat depth can thus be identified. The average peat depth at the transition from bog to fen was 0.67 m, with a range from 0 m to 1.52 m. Thus, where there has been no human disturbance to the system it is possible on average to have a bog vegetation supported by a peat thickness of 0.67 m, but in some cases it may require as much as 1.52 m of peat before ombrotrophic conditions prevail.

3.6.2.2 Individual site studies – spontaneous re-vegetation

Numerous descriptions have been published of cut-over sites which have undergone some form of spontaneous re-vegetation either without any management intervention or only following actions to block drainage. Some of these accounts are pre-cursors to active transplantation of vegetation but the effects of such intervention will be considered in Section 3.6.2.4 below.

Artz *et al.* (2008) [3+++] describe five cut-over sites from five different localities across Europe (Scotland, France, Finland, Swiss Jura and French Jura) and identify a range of 'regeneration stages' within these sites. The residual layer of peat ranges between 0.7 m and 3.1 m although a depth of 1-2 m is the commonest condition. In all, 17 regeneration stages are recognised across the whole suite of sites, of which 10 can readily be identified as poor-fen communities, 4 consist mostly of bare peat, 2 consist of dominant *Eriophorum vaginatum* and one has a vegetation which, though *Sphagnum*-rich, cannot be assigned to bog or fen because the *Sphagnum* species are not defined. Money (1994) [3+++] provides an account of 13 vegetation communities and numerous sub-communities which he identifies from examination of 17 cut-over bogs distributed across the UK, and one site in the Irish Republic. Recorded residual peat depths are mostly 1.5 m or more, although some have less than 1 m and there is 1 record of 0 m. Of these 13 vegetation types, Money (1994) assigns 10 to fen or woodland vegetation types, some of which are assigned to communities described by Rodwell (1991a,b). Money (1994) assigns two of his vegetation classes to two of Rodwell's (1991b) blanket mire communities and one vegetation class to Rodwell's (1991b) raised bog community. The conductivity values for all of Money's (1994) communities are very high – far higher than the 100 µS cm^{-1} recommended by Quinty and Rochefort (2003) as the boundary threshold between restoration to bog and restoration to fen, and in fact all three of Money's (1994) communities which he assigns to 'bog' vegetation classes contain significant numbers of fen indicators such as *Drepanocladus fluitans, Juncus bulbosus, J. effusus, Sphagnum squarrosum, S. fimbriatum, S. palustre* and *Potamogeton polygonifolius* – sufficient to make a strong case for assigning two of these to poor-fen communities described by Rodwell (1991b) and one to a wet woodland community (Rodwell 1991a).

Wheeler and Shaw (1995) [2++] undertook a survey of 43 cut-over sites, or sites where there had been some peat cutting, across lowland UK, the Republic of Ireland, the Netherlands and Germany. In some cases these sites involved small-scale hand-cutting on the margins of larger raised bogs. Species compositions are not provided nor, unfortunately, are values for residual peat depth. Particular species responses are noted, though in many cases the general terms Sphagna or *Sphagnum* are used so it is not possible to determine which species of *Sphagnum* are involved, the only species explicitly named being *Sphagnum cuspidatum*. Across these 43 sites, only some examples of hand-cutting are described as having re-developed a bog vegetation. All other references to species composition are to fen species, or to *Eriophorum vaginatum* and occasional mention of *Vaccinium oxycoccos* or *Calluna vulgaris*. Meanwhile, Meade (1992, 2003) [3++] describes the sequence of events when a formerly block-cut raised bog, which had become dominated by *Molinia caerulea* and *Betula pubescens* in many parts, was then re-wetted. This resulted in death of much *M. caerulea* and many of the birch trees, together with a large rise in abundance of *Drepanocladus fluitans*, *Sphagnum cuspidatum* and *S. fimbriatum* – producing extensive areas of semi-flooded poor-fen. Meade (2003) also describes a transplant experiment on the site, which is considered in Section 3.6.2.4 below.

McMullen *et al.* (2004) [3+++] investigate a number of raised bogs from England, Scotland and Northern Ireland, including one cut-over bog in South Cumbria – Arnaby Moss. This site was cut away for domestic fuel peat to a depth which exposed the underlying fen peat and has since revegetated with an almost continuous sward of *Sphagnum recurvum* and *Eriophorum vaginatum* tussocks, with, in places, low hummocks of *Sphagnum palustre*. McMullen *et al.* (2004) describe the vegetation as minerotrophic fen, particularly as the site now apparently receives fertilizer run-off from the surrounding fields. Vasander and Roderfeld (1996) [2++] provide an overview of spontaneous re-vegetation on three areas of milling on two peatland sites in Finland – Aitoneva I, Rastunsuo I and Rastunsuo II. At both sites the milling ceased because the undulating mineral sub-soil was starting to be exposed. At Rastunsuo the peat remained largely bare 9 years after commercial operations ceased and the situation was much the same at Aitoneva even after 20 years. Tuittila *et al.* (2000) [3+++] describe Aitoneva following restoration work begun in 1994 which involved blocking the drainage system and bringing in water from the surrounding peatland. They state that the residual peat layer was 1 m thick, and note that the bare peat was colonised by *Eriophorum* vaginatum tussocks while wetter areas were colonised by poor-fen Sphagnum species and *Carex rostrata*. They also note that the *C. rostrata* expanded much more rapidly than the *E. vaginatum*. Kivimäki *et al.* (2008) [3++] describe the site some years later and identify the continued presence of three broad vegetation groups – an *Eriophorum vaginatum*, bare peat and *Betula* scrub community found on the dryer peat, a *Sphagnum* community consisting poor-fen species, and a *Carex* community, again comprising a poor-fen assemblage, these latter two vegetation types occurring in the wetter areas of peat.

Maas and Poschlod (1991) [2+++] provide a review of re-vegetation responses on two cut-over sites in southern Germany – Wendlinger Filz and Kendlmühlfilzen. For the first site they indicate that species composition tends to retain fen species until the residual depth of peat exceeds 3 m, and that restoration of a bog community is only likely if it is initiated on raised bog peat. In the case of Kendlmühlfilz, which has a residual ombrotrophic peat depth of 0.5 m overlying a thicker layer of fen peat, they undertook restoration planting so this will be considered under Section 3.6.2.4, but Sliva *et al.* (1997) [3++] record a number of species which colonised the study area spontaneously and these are (with the arguable exception of *Drosera rotundifolia*, which can, however, grow on base-poor mineral soils) all poor-fen or even mesotrophic fen species.

In Canada, D'Astous *et al.* (2013) [2+], in their study of species introduction, note simply that the milled areas of Bois des Bels, which has a residual peat depth of 1.7 m, had a 'mesic' vegetation (i.e. fen vegetation) prior to the area being prepared for experimental work. Poulin *et al.* (2013) [3+++] also note that the restoration area of Bois des Bel has significant non-peatland vegetation components including wetland species and woodland. They show that the fen species *Typha latifolia* and *Calamagrostis canadensis* have increased across the restored field, not merely in the ditches, as have species typical of bare peat, although all show signs of a decline towards the end of the 8-year reported monitoring period, which Poulin *et al.* (2013) suggest might be as a result of expansion from more typical 'peatland' species, as reported by McCarter and Price (2013) – which will be considered in more detail in Section 3.6.2.4. Meanwhile Malloy and Price (2014) [3+++] describe a restoration programme undertaken on Bic-Saint-Fabien, Quebec, where the residual peat layer varied from 0.4 m to more than 1 m and consisted of fen peat. The decision was therefore made to restore the site to fen rather than bog.

3.6.2.3 Multiple-site studies of spontaneous re-vegetation

Several large-scale studies of vegetation recovery on cut-over sites have been undertaken in which the results from the various sites have been pooled so that it is no longer possible to identify individual site responses but the overall trend from the collection of sites is highlighted.

Wheeler and Shaw (1995) [2++] review the range of vegetation types reported to occur on cut-over raised bogs in the UK and identify four broad vegetation classes:

- 'bog-*Sphagnum*' vegetation, which is described as *Sphagnum*-rich vegetation similar to natural bog vegetation; the sites given as examples are those which have small-scale hand-cutting or long-abandoned block-cutting of peat;
- 'para-bog-*Sphagnum*' vegetation, which is described as a vegetation containing many species found in bog vegetation but not in the same proportion; the example sites given are, or contain, areas of long-abandoned areas of block-cutting;
- 'dry bog' vegetation, which contains few typical bog species and is closer to heath, poor-fen or wet woodland; the example sites given have areas of old hand-dug cuttings and/or areas of long-abandoned block-cutting;
- fen vegetation; a large range of fen vegetation types is presented, together with the observation that a wide variety of fen vegetation is recorded from UK peat cutting sites because fen develops when peat removal exposes the lower fen-peat layers or permits ingress of minerotrophic water.

Unfortunately Wheeler and Shaw (1995) do not provide any indication of the way in which residual peat depth may relate to the presence or absence of these vegetation types, nor do they relate the types to forms of peat cutting – e.g. hand-cutting vs. milling – nor is any idea of extent covered by the various types given. It is difficult to know whether, for example, 'bog-*Sphagnum*' only occurs in a few limited areas exclusively in hand cuttings, or whether it is widespread on restored milling fields. Equally, it is not clear whether the wide variety of fen types recorded from UK cut-over bogs indicates that fen vegetation is widespread in such sites.

In their study of 11 milled-peat sites in the Czech Republic, Konvalinkova and Prach (2014) [3+++], meanwhile, found that 70% of their quadrats contained at least one fen species whereas only 10% of quadrats contained at least one raised bog species. The commonest bog species was *Eriophorum vaginatum* while other typical raised bog species for the Czech Republic (such as *Vaccinium uliginosum* and *Ledum palustre*) were found only rarely. The commonest *Sphagnum* was *S. fallax*, and *Sphagnum* as a whole was only recorded from 8% of quadrats, most typically occurring in wet areas with a pH of between pH5.2 and pH5.8 and with a residual peat thickness ranging from 0 m to more than 1 m. From this it is clear that the main occurrence of *Sphagnum* was largely restricted to poor-fen conditions.

Girard *et al.* (2002) [3+++], in their survey of spontaneous re-vegetation within block-cut and milled areas of Cacouna Bog, Quebec, found that *Sphagnum* and most ombrotrophic species were most abundant in the block-cutting trenches which had been most recently abandoned, while the milled peat fields had only a 10% cover of *Sphagnum*. Species composition overall was most influenced by water table, residual peat depth and pH, with several *Sphagnum* species being characteristic fen species (e.g. *S. fallax, S. fimbriatum* and *S. lindbergii*). Girard *et al.* (2002) conclude that successful *Sphagnum* colonisation requires that the water table never falls more than 40 cm below the peat surface.

Gonzáles *et al.* (2014) [3+++] surveyed a range of block-cut peatlands in the Bas-Saint-Laurent of Quebec, gathering data for residual depth of peat, water table, pH, conductivity and degree of humification. Specifically they were looking at the vegetation response following re-wetting of the three study sites at differing stages after re-wetting – 4 years after for Cacouna Bog, 10 years for Saint Laurent and 17 years for Isle Verte. They found a marked increase in cover of poor-fen *Sphagnum* species, including *S. fallax, S. riparium* and *S. angustifolium*. No similar increase was observed for any more ombrotrophic species such as *Sphagnum fuscum* or *S. rubellum*. They speculate that, in time, these poor-fen *Sphagnum* communities may come to be colonised by more ombrotrophic species.

Like Konvalinkova and Prach (2014), Poulin *et al.* (2005) [3+++] found that spontaneous colonisation of milled fields by *Sphagnum* was slow. From the 394 milled fields sampled, only 21% had any *Sphagnum* colonisation and the total cover did not exceed 10% except on two occasions, when it exceeded 25%. The commonest species was *Sphagnum rubellum*, which is a typical species of raised bogs, although the second-most common species was *S. fallax* which is a species of poor-fen environments. Perhaps counter-intuitively they found a weak indication that spontaneous *Sphagnum* colonisation diminished with increasing residual peat thickness, which they attribute to the greater dryness of the deeper peats.

Taylor and Price (2015) [3+++] investigate the water-table behaviour of regenerated *Sphagnum* carpets of differing species composition and age. They identify that in thin Sphagnum carpets the position of the water table in the cut peat layer beneath the regenerated carpet is the key to maintaining moisture within the carpet, but as the carpet thickens to >15 cm this dependency diminishes and precipitation becomes the key factor, at least for species such as *Sphagnum magellanicum*. In the case of *S. rubellum*, however, the connection with the underlying water table was not lost and suggests that this species is capable of drawing on water from the water table through capillary action during periods without precipitation while benefitting from precipitation inputs when they occur, whether as measurable precipitation or occult precipitation. They suggest that establishment of a hydrologically self-sustaining *Sphagnum* layer is the key goal for ombrotrophic bog restoration.

Triisberg *et al.* (2014) [3+++] investigated the spontaneous re-vegetation of 64 peatlands and 114 milled peat fields within these peatlands. They obtained data for residual peat depth, humification at differing layers, water level, pH and mineral content as well as detailed vegetation data. They distinguished between the fields themselves and the drainage ditches running through the fields. Their results suggest that there are several successional pathways for spontaneous colonisation of milled-peat surfaces by vegetation, but for the vegetation to develop into a typical ombrotrophic bog vegetation then a thick layer of slightly-decomposed peat is required, otherwise the tendency is towards development of fen vegetation. They conclude that the critical threshold is a residual depth of 2.3 m. For peat depths less than 2.3 m the natural tendency will be for fen species to establish and form a vegetation cover whereas if the peat is greater than 2.3 m deep then direct development of an ombrotrophic bog vegetation will be possible.

3.6.2.4 Restoration studies involving active transplants of species

Money (1994, 1995) [3+++] investigated the growth under various conditions of several species of *Sphagnum* on an inclined bare-peat slope which was partly inundated. He tested

S. magellanicum, S. papillosum, S. capillifolium, S. palustre, S. fimbriatum, S. recurvum, S. auriculatum and *S. cuspidatum*. In addition, *S. cuspidatum* and *S. recurvum* were macerated and applied to the peat slope, and, as a further experiment, these two species were tested for their response to additions of nutrients and lime. Only the aquatic *S. cuspidatum, S. recurvum* and *S. auriculatum* survived the experiments, with these three growing vigorously, although addition of lime tended to produce a check in growth. This set of experiments serves to emphasise both the aquatic and poor-fen affinities of these three species, but appears to offer little promise for the more ombrotrophic species of *Sphagnum*.

Meade (2003) [3++] adopted a similar approach to Money (1994) at Danes Moss, Cheshire, in using an inclined, partially-inundated, slope but used an existing ditch instead. He also investigated the 'nurse' effect of *Molinia caerulea* tussocks across the general peat surface. He applied *Sphagnum papillosum* to these two types of environment in a series of small-scale quadrats and found that the *S. papillosum* performed best in the *Molinia* tussock environment, which was 5x more successful than the area of intermittently-inundated bare peat. He therefore concludes that re-vegetation via a damp peat surface through the process of 'paludification', as recommended by Lindsay (2003), is likely to be a more effective approach to re-vegetation than that of, in effect, 'poor-fen terrestrialisation' where aquatic *Sphagnum* species are encouraged to develop over inundated conditions.

Maas and Poschlod (1991) [3+], Sliva *et al.* (1997) [3++], Sliva and Pfadenhauer (1999) [3+++] and Poschlod *et al.* (2007) [3++] present data from a small set of block-cut and milled sites located to the south of Munich in southern Germany. They use these sites to provide a sequence of possible restoration strategies:

- spontaneous re-vegetation in block-cut peat without any intervention, but where the vegetated surface was placed down in the cut trench during cutting;
- spontaneous re-vegetation on milled peat without any intervention;
- spontaneous re-vegetation in block-cut peat with re-wetting;
- vegetation transplants on re-wetted milled peat.

In the case of non-intervention block-cut peat which had been abandoned in 1960 (Wieninger Filz), fresh *Sphagnum* moss of up to 80 cm had already accumulated by 1986, produced by *Sphagnum papillosum, S. cuspidatum* and *S. angustifolium*, and by 2006 a mixture of *S. papillosum* and *S. magellanicum* had added a further 28-30 cm. Areas with *S. angustifolium* and *Eriophorum vaginatum* dominance had added no fresh peat, however. Milled areas abandoned in the mid-1980s (Wendlinger Filz) without management developed three distinct vegetation communities depending on degree of inundation and water/peat chemistry. Driest acidic areas were colonised by *Eriophorum vaginatum*, moist areas of less acidic peat supported vegetation dominated by *Rhynchospora alba*, and wet areas of mesic peat and water supported stands of *Carex rostrata, Eriophorum angustifolium* or *Phragmites australis*. This remained the position in 2006. The block-cut site (Wurzacher Ried) which was re-wetted only developed floating mats of (in effect poor-fen) *Sphagnum*, losing established swards of *S. magellanicum* and seeing a rise in cover of *Carex rostrata* and *Phragmites australis*. On Kendlmühlfilz the milled area was sown with *Carex rostrata, Eriophorum angustifolium, E. vaginatum* and sods of *Sphagnum*. After 4 years the *C. rostrata* had covered almost the entire transect whereas the *Eriophorum* species had not expanded at all while some *Sphagnum* died and some expanded. At this site in particular it proved impossible to control upwelling of minerotrophic water through the thin ombrotrophic peat layer, which has limited the range of species which have established successfully.

Karofeld *et al.* (2015) [3+++] give a detailed account of a restoration experiment carried out on a milled raised bog in Estonia (Tässi Bog) which involved using the 'moss layer transfer method' described by Quinty and Rochefort (2003). Tässi Bog was chosen for the experiment because it retains a residual peat thickness of some 2.5 m including 1 m of ombrotrophic peat – as recommended by Triisberg *et al.* (2014) discussed above. The top 20 cm layer of oxidised peat was first stripped from the surface and two level areas were established, one slightly higher than the other. The water table rarely fell below -40 cm and never below -45 cm during the period of the study. It was found that stripping the top 20 cm significantly enhanced *Sphagnum* success, while *S. rubellum* and *S. fuscum* were better at coping with lowered water tables than *S. magellanicum*. The experiment achieved 60% cover of these target *Sphagnum* species within 3 years.

Price *et al.* (1998) [3+++] give details of a re-vegetation experiment undertaken on a residual plateau raised bog peat deposit with a thickness ranging from 1.2 m to 1.8 m in the Lac-Saint-Jean area of Quebec. The peat layer had experienced oxidation and compression during mining operations. The drains were blocked and the surface levelled and then re-shaped into a set of small-scale micro-reliefs. Shredded vegetation from an area dominated by *Sphagnum fuscum* and an area dominated by *S. angustifolium* was then applied to the peat surface. Some parts of the experimental area were then covered with mulch. The mulched area was found to maintain pore-water pressure above -100 mb and retain the water table at a higher level than areas without the mulch, although not wholly above the critical -40 cm throughout the year which is now thought to be necessary for successful *Sphagnum* establishment. After one growing season, *Sphagnum* cover had nevertheless reached 5-7% cover, although no information is provided about the relative success of the two species – one an ombrotrophic bog species (*S. fuscum*) and the other (*S. angustifolium*) a species of both poor fens and depressions in bogs.

McCarter and Price (2013) [3+++] undertake a detailed study of the *Sphagnum* introduction experiment begun on Bois des Bel, Quebec, in 1999. In 10 years the milled peat surface had almost 100% coverage of *Sphagnum capillifolium* (although *S. fuscum* had been applied at the start too). Poulin *et al.* (2013) [3+++] (discussed above) have identified that despite this cover the vegetation assemblage still contains a significant number of 'non-peatland' (and indeed 'non-bog') species. McCarter and Price (2013) identify that there are in fact now two water tables on the restoration site – the first is the water table within the original cut-peat surface, into which many of the 'non-bog' vascular plants presumably still root, while a second perched water table has developed within the *Sphagnum capillifolium* carpet. McCarter and Price (2013) speculate that as the *Sphagnum* layer accumulates more material the water table in the carpet will merge downwards to join with the 'old' water table, at which point the surface may become increasingly, truly ombrotrophic. They offer no timescale for this process.

Finally, Quinty and Rochefort (2003) [2+] in their Appendix A provide a summary of restoration or reclamation activities associated with 17 cut-over sites distributed across Canada. Of these they are able to provide information concerning vegetation responses and associated residual peat depths for 10 sites. Unfortunately, rather like Wheeler and Shaw (1995) the only vegetation information provided consists of generic words such as Sphagnum, wetland, vegetation and plant establishment. It is only therefore possible to obtain a picture of whether some form of vegetation has established but not whether it is bog vegetation. Despite the absence of more detailed vegetation information, it is instructive to look at the information provided by Quinty and Rochefort (2003) about these transplant restoration cases because they provide values for peat depth and give an indication of the re-vegetation response. This information is therefore collated in Table 7.

Table 7. Information concerning the re-vegetation of cut-over sites in Canada, taken from Quinty and Rochefort (2003). Unfortunately no more information is provided about the vegetation type than is given in the present table so distinctions between development of bog and fen vegetation are not possible, only possible presence of peat-forming vegetation.

Site	Peat Depth (m)	Vegetation type
Pit Bog	0.5	Fen species on margins, bog species in centre, almost no *Sphagnum* growth despite transplants
Maisonnette	0.15- 1.0	Low plant establishment in first 2 years; generally less than 12% cover.
Saint-Henri	0.3 – 0.5	Some dry sectors with no vegetation; some areas of wetland with *Sphagnum*.
Chemin-du-Lac	0.3 – 1.0	Good plant establishment; 80% cover
Baie-Sainte-Anne	0.5	Transplanted plant fragments died; low success of further introductions.
Saint-Charles	0.35 – 1.25	Mineral sub-base exposed along ditch bottoms; good plant colonisation but high species diversity due to enrichment.
Sainte-Margueritte	>1.0	Vegetation cover of higher plants, and *Sphagnum* successfully established.
Rivière-Ouelle	1.2	Good results after 3 years.
Bois-des Bels	1.0 – 3.0	Vegetation establishment rapid from the start.
Inkerman Ferry	>1.75	Good establishment of plants in first 2 years.

3.6.3 Synthesis

There is **strong** and **consistent** evidence to show that there are not yet any successful cases of managed restoration to ombrotrophic bog vegetation in the UK. This is also true for restoration programmes in Germany, the Netherlands and Canada. In all these localities, restoration has been undertaken on cut-over bogs where the residual depth of peat has been less than 2 m.

This contrasts with Estonia where there is **strong** evidence that spontaneous re-establishment of bog vegetation has occurred on cut-over bogs in Estonia which have a residual peat depth greater than 2.3 m.

There is also a **strong** indication from experimental evidence that milled bog surfaces which retain more than 2.3 m of residual peat (including some ombrotrophic peat) are capable of establishing an ombrotrophic *Sphagnum* sward directly.

There is **strong** evidence to show that the thinner the peat layer (and the more likely it is to have exposed fen-peat layers) the stronger the tendency for a restored vegetation to be dominated by fen species.

There is **strong** evidence to indicate that a residual peat layer of 0.5 m thickness, whether strongly-humified or not, will not give rise to ombrotrophic raised bog vegetation without first passing through a fen phase.

If there is a strong possibility that a 0.5 m residual peat layer will give rise to poor-fen vegetation rather than ombrotrophic bog, one important question would be the time such poor-fen systems may require in order to develop into bog habitat. This question of successional timescale forms the focus of the next sub-question.

3.7 Sub-Question 5: What is the timescale of transition from poor-fen conditions to ombrotrophic bog in natural or managed peatland succession?

3.7.1 Background

Given that much commercial peat extraction tends to leave only the thinnest of peat layers as a residual peat layer, concerns have been expressed that attempts to restore bog habitat on such a peat layer may instead be diverted into the development of poor fen habitat because the residual peat layer consists of fen peat. This is a particular concern given the timescale of around 30 years for successful restoration to raised bog habitat looked for under the terms of the EU Habitats Directive. Unfortunately there are few peat bog restoration programmes in Britain which have been running for even 30 years, particularly given that the process of peat milling only really became established as the favoured technique for industrial peat extraction in the 1980s. Most UK studies of restoration after peat milling have so far necessarily been of relatively short duration.

Although the current peat extraction industry has only existed for a little over 30 years in its present form, peat extraction has been undertaken on something close to industrial scales for centuries and in some places it is possible to see that a process of natural succession has taken place within these abandoned working. Meanwhile many peatlands sites have been undergoing the process of natural succession almost since the end of the last ice age. Consequently it is possible to examine areas of old abandoned peat cutting, and look at the successional processes which natural peatlands have undergone in the past, in order to obtain some sense of the timescales involved in the process of transformation from poor-fen habitat to ombrotrophic bog.

Indeed a significant body of literature has grown up around the current condition of old peat cuttings. Sometimes the patterns of succession which they contain within their fresh peat archives have been examined. Meanwhile the natural succession from fen to bog which occurred in the early stages of many raised bogs offers another perspective, although the ability to draw conclusions about the timescales involved in relies on the presence of measured time-markers, such as radiocarbon dates or the presence of known and dated tephra deposits. While such time-stamps are relatively rare in published literature for that period of bog development, they are not entirely absent and can thus be compared with successional responses observed in old peat cuttings.

3.7.2 Categorisation and assessment

Information relevant to this Sub-Question was examined in detail for 12 publications. Of these 12 publications, 6 were quantified field descriptions which provide measured values for the duration of succession from fen to bog and were thus categorised as 3+++. Two studies gave measured field data but no detailed vegetation data and were thus classed as 3++. Two reviews gave measured examples but provide no background supporting data and were thus classed as 2+++. Two reviews provided only cited comments about vegetation or indicated timescales without explicit supporting information and were thus classed as 2++.

3.7.2.1 Duration of the natural fen-to-bog (FTB) transition

Walker (1970) [2+++] provides a review of post-glacial hydroseres and presents a table indicating the duration of various hydrosere stages. The duration for transition from open water to bog ranges from <500 years at Scaleby Moss, Cumbria, to 1,500 years for Oulton Moss, also in Cumbria. In recent years the natural FTB of raised bogs has attracted a certain amount of interest because there is a growing body of evidence to suggest that this transition phase is sometimes an abrupt phase in which the bog surface appears to dry out before becoming dominated by a wet *Sphagnum*-rich assemblage (Hughes, 2000). Hughes *et al.* (2000) [3+++] show that the *Sphagnum palustre* poor-fen phase at Walton Moss, Cumbria lasted between 200 and 600 years. Hughes and Barber (2003) [3+++] demonstrate that the poor-fen *S. palustre* phase at Cors Caron (Tregaron Bog), Ceredigion, lasted 90 years, whereas this same phase lasted for 300 years at Bolton Fell Moss, Cumbria and an average of 290 years for three other Cumbrian raised bogs. Hughes and Barber (2004) [3+++] indicate that a similar timescale applies to Abbeyknockmoy Bog and Mongan Bog in the Republic of Ireland.

3.7.2.2 Evidence for duration of FTB in restoration of cut-over mires

Joosten (1995) [2+++] cites examples of hand-dug peat pits in the Kulbinger Filz of Southern Germany, where a 40 cm thickness of fresh peat has accumulated over a 60-year period from a *Sphagnum recurvum-Carex rostrata* poor-fen community in which there are some pockets of more ombrotrophic bog vegetation. He also reports that Thorne Moors, Humberside, still does not support any bog vegetation in re-vegetated peat cuttings abandoned more than 70 years previously. Joosten (1995) also presents data assembled by Lütt (1992) for a set of hand-dug peat pits in Schleswig-Holstein in which the bottom of the regeneration layer is dated. Basal dates range from 41-100 years and for most of these pits it appears that transition to a *Sphagnum magellanicum* or *S. papillosum* community has occurred only in recent times. Indeed one 41-year pit still shows no change from the initial *S. cuspidatum-Eriophorum vaginatum* poor-fen stage. Joosten (1995) observes that, apart perhaps from some mountain mires, he knows of no example where an industrially mined peatland site has been restored to functioning ombrotrophic bog conditions – an opinion echoed by Gorham and Rochefort (2003) [2++].

Artz *et al.* (2008) [3++] provide minimum ages for the plant communities detailed in their review of five cut-over sites scattered across Western Europe and discussed earlier in Section 3.6.2.2. The youngest of the vegetation groups is less than 5 years old, but there is one site which is more than 50 years old where the vegetation is a poor-fen community dominated by *Sphagnum fallax, Polytrichum strictum, Eriophorum vaginatum* and *Vaccinium* spp., while another community of at least 42 years is much the same. There are communities which are at least 21, 22 or 29 years old yet all are dominated by *Sphagnum fallax*. One 50-year community is described as having *Sphagnum* spp. with *Calluna vulgaris* and *Deschampsia flexuosa*, and such a mix of vascular plants would suggest that the *Sphagnum* is yet again *S. fallax*. Most of these sites are on more than 1 m of residual peat.

The review by Wheeler and Shaw (1995) [2++] of restoration activities across 43 cut-over sites in the UK, Ireland, the Netherlands and Germany includes a date for the start of restoration works. The earliest of these is dates from the 1930's for Weininger Filz in Southern Germany – a site discussed above in Section 3.6.2.4 – and involves the revegetation of hand-dug peat pits. The earliest dates for industrial-scale peat extraction are the 'early 1970's' and 1974, for Crowle Moors (Humberside), and Danes Moss (Cheshire). The latter site has already been described under Section 3.6.2.2, indicating that poor-fen vegetation still dominated the site 14 years after re-wetting, and Wheeler and Shaw (1995) note that in the early 1990s it was still dominated by poor-fen communities. Wheeler and Shaw (1995) describe the vegetation at Crowle Moors as: "Floating rafts in old peat cuttings (including Sphagna, *E. angustifolium* and *Vaccinium oxycoccos*)." 'Floating rafts' can be assumed to be *S. cuspidatum* or *S. recurvum* and thus representing a poor-fen habitat because few other *Sphagnum* species found in this kind of environment behave in that way. Nowhere (apart from the very old peat pits) does this list of restoration actions, dating back more than 20 years at the time of publication, offer an example of successfully restored bog vegetation.

Money and Wheeler (1999) [2++] reviewed progress to date in the restoration of cut-over raised bogs. They noted that the best examples of regenerated bog were found in old hand-dug peat cuttings which had re-colonised' "often within less than 100 yr." They also noted that later-successional stages had not yet appeared extensively in most abandoned peat workings, and lagoon-style restoration efforts using poor-fen rafts of *Sphagnum recurvum* or *S. cuspidatum* had shown a similar disinclination to move on to later successional stages. They refer to certain examples of vigorous *Sphagnum* development but do not identify the species, and indeed they refer to restoration approaches through terrestrialisation as perhaps "a leap of faith?"

In something of a contrast to both Wheeler and Shaw (1995) and Money and Wheeler (1999), Lucchese *et al.* (2010) [3+++] consider the extensive *Sphagnum rubellum* carpet which has been established across Bois des Bel milled raised bog in Canada using the 'moss layer transfer technique' pioneered in Quebec using, in effect, a paludification process. Lucchese *et al.* (2010) identify that after 7 years the *Sphagnum* carpet had developed a thickness of 19 cm across 23% of the site. They regard 19 cm as the threshold for a *Sphagnum*-rich acrotelm to be capable of containing water table fluctuations and thus become self-sustaining. On the basis of the development rate to 2007, Lucchese *et al.* (2010) estimate that the site may develop a complete and functioning acrotelm in a further 17 years. This, it should be noted, is on a site which has somewhere between 1.5 m and 1.8 m of residual peat and still supports a number of fen species. It is also worth noting that 3 years later, McCarter and Price (2013) [3+++] were unable to say when the moss-layer water table would merge with the water table of the cut-over peat beneath, as observed in Section 3.6.2.4 above.

Karofeld *et al.* (2015) [3+++] are also able to demonstrate rapid establishment of ombrotrophic bog Sphagna, albeit so far with initially limited cover, within a single growing season on a residual peat layer which is 2.5 m thick including a 1 m layer of ombrotrophic peat, thereby avoiding the likelihood of undergoing a fen phase initially. After three years the target *Sphagnum* species had achieved a cover of more than 60%.

Written a decade earlier than McCarter and Price (2013), Gorham and Rochefort (2003) [2++] speculated that: *"...a significant number of characteristic bog species can be established in 3-4 years, a stable high water table in about a decade, and a functional ecosystem that accumulates peat in perhaps 30 years."* This comment is made within the Canadian context, where it is not unusual to leave a residual peat layer more than 1 m thickness because the main raw material of the industry is relatively un-decomposed *Sphagnum* peat which is generally found in the upper layers of a bog.

3.7.3 Synthesis

There is **strong** evidence to show that no milled raised bog in the UK has yet been restored to ombrotrophic bog conditions as a result of a restoration programme.

There is **strong** evidence to suggest that succession from industrial-scale poor-fen vegetation to ombrotrophic bog conditions is likely to take at least 100 years.

There is **strong** evidence to support the suggestion that direct establishment of ombrotrophic bog Sphagna is possible if the residual layer of peat is sufficiently deep (>2 m) and includes a significant thickness of ombrotrophic peat.

3.8 Sub-Question 6: What are the potential effects on a bog restoration programme of using a residual peat depth having an average minimum depth of 0.5 m?

3.8.1 Background

As part of the ROMP process, various planning consents for commercial peat extraction are currently being reviewed by planning authorities or are due to be reviewed in the foreseeable future. Some consents already have a condition in place (e.g. Springfield Moss, Penicuik, Midlothian) which states that *"...a minimum average depth of in situ peat of 0.5 m shall be retained at the cessation of peat extraction."* According to the Restoration Plan Version 2 for this site (Terraqueous Ltd, 2015), this minimum average depth would be achieved by dividing the site into 1 ha squares, measuring the peat depth randomly once within each square, then ceasing work within an operational compartment when the peat depth "is equal to 0.52 m or less" if averaged across all such measurements taken within that compartment.

It is not immediately clear why the final words "or less" are required because this places no limit on how much less this calculated average is allowable. Complete removal of the peat would still meet the requirement for an average calculated across all readings to be "0.52 m or less."

Furthermore, even if the words "or less" are discounted, this method of calculation allows parts of a compartment to have the peat removed completely provided there are sufficient other measurements within the compartment to generate an average depth of 0.52 m. This is an entirely feasible scenario if the mineral sub-soil is sloping or undulating.

It is clear from the information presented in relation to Sub-Questions 1-5 that a significant body of relevant evidence is available concerning the specific question of an 'average minimum residual peat depth of 0.5 m'. Much of this evidence has already been reviewed and discussed above. Little would be gained by repeating this evidence here, but there are also other factors which do merit consideration at this point.

3.8.2 Categorisation and assessment

Information relevant to this Sub-Question was examined in detail for 24 publications. Of these 24 publications, 13 were experimental studies or quantified field descriptions which provide detailed information relatable to the impacts of adopting an average minimum depth of 0.5 m, and were thus categorised as 3+++. Two publications were field investigations which gave indirectly relevant information and so were classed as 3++. One publication described a field site and noted relevant information and was thus classed as 3+. One publication provided an in-depth review of water-table behaviour in highly-decomposed residual peat layers and was thus classed as 2+++. Five publications were reviews which provided some field evidence of other tangible evidence and were thus classed as 2++. Two publications were reviews which put forward arguments or thresholds but provided no actual supporting evidence and were thus classed as 2+.

3.8.2.1 Complete loss of peat in places

An 'average' by its very nature implies that some values will be greater than a given number and other values will be less than this number. Setting aside for the moment the somewhat illogical concept of having values which are less than a 'minimum', and also the curious use of the words "or less" in Terraqueous's (2015) description of the method, the apparent process for defining an average minimum depth of peat inevitably means that some parts of an operational compartment will have little or no peat under this process. A great many profiles of raised bogs reveal that the underlying mineral sediments of a raised bog are rarely a smooth flat or concave surface (e.g. Wheeler and Shaw 1995, Fig.1.1; Gore 1983, Fig,1.3; Taylor 1983, Fig.1.21; Botch and Masing 1983, Figs. 4.11, 4.14, 4.19, 4.21; Sliva *et* al. 1997, Fig.32.4; Rydin and Jeglum 2006, Fig.7.3). All these profiles are classed as 3+++. With an undulating mineral subsoil, the method of 'average minimum depth' will inevitably lead to some areas having all peat removed even though the 'average minimum depth' never becomes less than 0.52 m. That such undulations result in loss of all peat in places is, for example, recorded by Vasander and Roderfeld (1996) [2+] at Aitoneva and Rastunsuo raised bogs in Finland.

Exposure of the peat within a milling field is no different from a ditch which cuts into the mineral subsoil – something which all authorities say should be guarded against. Not only will any such mineral exposure provide the opportunity for minerotrophic water to influence the restoration surface and its vegetation, but unless a careful survey of the underlying subsoil has been undertaken it also opens up the possibility of either providing a source of drainage or of groundwater upwelling as experienced at Kendlmühlfilz in Bavaria – leading to extensive fen development. The site case-study records of Morgan-Jones *et al.* (2005) [3+++] highlight the highly variable nature of mineral subsoils beneath many UK raised bogs.

3.8.2.2 Shrinkage of the residual peat layer

During the final five or six years of operational milling, the peat body which will make up the final residual peat layer will be subject to pressures from gravity-driven drainage and evaporation during the period that the milled peat is drying on the milling field. The peat in these lower layers of a raised bog is almost certain to be at least moderately humified, while the general recommendation for peatland restoration is that it should be strongly humified. Drainage effects will result in subsidence due to secondary compression (and possibly also primary consolidation if the slit-drains or main drains are deepened during these years) as well as oxygen penetration and resulting peat decomposition (Hobbs, 1986) [2++]. These together will cause reduction in peat volume by collapsing the smaller peat particles (smaller as a result of decomposition) more closely together. The more humified the peat, the more it will shrink in response to drainage pressures, with peat of H7 potentially losing 50-60% of its volume by shrinkage (Graham and Hicks, 1980) [3+++].

This shrinkage has two important effects. Firstly it reduces the 'average minimum depth' to something less than the value obtained when actually measured. All the while that the drainage system remains un-blocked and operating, the peat will be draining and shrinking, reducing the calculated 'average minimum depth' to something less (potentially significantly less) than the target 0.52 m thickness by the time restoration measures are begun.

Secondly, the more the peat shrinks, the more it will crack (Pyatt *et al.*, 1987 [3++]; Blankenburg and Kuntze (1987) [2++]; Schouwenaars (1993a) [2++]; Blankenburg (2004) [2++]). This provides pathways for water to drain from the surface layer of the peat (exactly where water is needed if *Sphagnum* is to be established) and potentially even be lost from the site through the mineral subsoil. It also provides a means whereby rainwater can penetrate to the mineral subsoil, fill the crack and then spill out over the peat surface during periods of heavy rain. Such minerotrophic enrichment has been a problem on many restoration sites (e.g. Sliva and Pfadenhauer, 1999 [3+++]).

3.8.2.3 Preparation of the surface layer for restoration

Karofeld *et al.* (2015) [3+++] describe how they removed the top 20 cm of the peat surface prior to establishing their *Sphagnum* restoration experiment. They emphasise the fact that stripping off this mineralised layer significantly improved *Sphagnum* growth. If the 'average minimum depth' of peat is only 0.5 m (and some of this depth may have already vanished through shrinkage), then stripping off 0.2 m to prepare the surface for *Sphagnum* colonisation as part of the restoration programme then reduces the peat thickness to a *maximum* of 0.3 m – but in practice probably to something less because of shrinkage.

Given that, using the ‘average minimum depth’ principle, some patches of ground are almost certain to have reached the mineral subsoil simply because of the undulating nature of the mineral sub-surface sediments, this combination of factors renders the residual peat layer very much thinner and more sporadic than is intended within the TandC planning process, but also renders the prospects for direct establishment of ombrotrophic bog virtually impossible.

3.8.2.4 Hydrological character of the residual peat layer

Price *et al.* (2003) [2+++], McCarter and Price (2013) [3+++] and Taylor and Price (2015) [3+++] emphasise the constraints imposed on *Sphagnum* re-establishment by the hydrological properties of a humified bare peat surface. A highly humified, shrunken and thus compacted, thin layer of peat will give rise to a water table which fluctuates to an extreme degree, potentially dropping out of the peat layer altogether at times if the residual peat layer is not thick enough. Such peat also generates pore-water pressures which render it impossible for *Sphagnum* plants to retain water within their hyaline storage cells, thus depriving the plants of the moisture which they require to survive. Under such conditions the re-establishment of ombrotrophic *Sphagnum* is certain to be extremely challenging, if not impossible, particularly given other factors such as potential nutrient enrichment as a result of exposed mineral surfaces, peat cracking or because the residual layer has exposed the basal fen peat.

Money and Wheeler (1999) [2+] suggest that recent research casts doubt on Wheeler and Shaw’s (1995) [2++] recommendation that for bog restoration a minimum of 0.5 m of *ombrotrophic* peat [their emphasis] should be retained. They also indicate (given the failure of all restoration schemes reviewed by them to produce anything other than “enormous bog pools rather than true bog”) that the most pragmatic option may be to re-establish poor-fen conditions in the hope that ombrotrophic bog conditions will develop in due course. If this course of action were to be adopted an ‘average minimum peat depth of 0.5 m’ would not necessarily present problems. Exposure of mineral sub-soil and inputs from mineral-enriched groundwater would be acceptable, merely influencing the likely duration of the fen phase before ombrotrophic conditions might start to become established. On the other hand, any areas where the mineral sub-soil was relatively porous would then be more likely to be a source of water loss from the site either through direct exposure of such mineral deposits or because thin peat is more likely to suffer cracking which reaches to the mineral sub-soil (Blankenburg and Kuntze 1987 [2++]).

The reviews of Wheeler and Shaw (1995) and Money and Wheeler (1999) are hampered in their scope and range of suggested solutions, however, by the lack of restoration examples involving residual peat depths of 2 m or more and of examples where a significant thickness of ombrotrophic peat has been retained. By default, their reviews are dominated by restoration studies in which the principle of ‘average minimum depth’ has in practice been a common factor in determining when peat extraction would cease. In addition, most of the studies reviewed by Money (1994) [3++], Wheeler and Shaw (1995) and Money and Wheeler (1999) approached the process of restoration through the colonisation (‘terrestrialisation’) of large bog hollows leading to a starting point of poor fen, rather than attempting the direct establishment of hummock-forming *Sphagnum* species on the general peat surface (‘paludification’).

Money and Wheeler (1999) [2+] acknowledge the possibility of paludification as a restoration approach and note the experimental work on this being undertaken at the time in Canada, but question the likely success of the method. The intervening years have shown that hummock-forming *Sphagnum* species can indeed be re-established through paludification (McCarter and Price, 2013 [3+++]), although the results in Canada have not generated a wholly ombrotrophic vegetation, most likely because the residual peat depth on these sites is less than 2 m. Since those early years of the last decade the thrust of restoration work in Canada has generally been towards direct development of ombrotrophic bog rather than seeking to pursue ombrotrophic bog development via a fen phase.

3.8.3 Synthesis

There is **strong** evidence to show that an 'average minimum residual peat depth of 0.5 m' would involve exposure of the mineral sub-peat deposits in at least some places.

There is **strong** evidence to show that an 'average minimum residual peat depth of 0.5 m' created at the time of cessation of commercial peat working would become significantly less than this thickness through drainage-induced subsidence between cessation of commercial extraction and blocking of the drainage system as part of a restoration plan.

There is **strong** evidence to show that thin peat layers subject to drainage are prone to cracking and that this cracking is more likely to reach the mineral sub-peat deposits if the peat is less than 0.5 m thick.

There is **strong** evidence to show that a thin, highly-humified peat layer possesses a water table which fluctuates to an extent that at times causes the water table to fall out of the thin peat layer altogether into the mineral sub-soil beneath, and that such a hydrological regime is not conducive to *Sphagnum* colonisation and survival.

There is **weak** evidence to support the suggestion that development of poor-fen conditions on a thin layer of residual peat is a viable means of restoring ombrotrophic bog conditions over any meaningful timescale.

There is **no** evidence either proposing or supporting the principle of an 'average minimum residual depth of peat' of any depth whatsoever. **All** published authorities refer explicitly to a *minimum* residual peat depth.

4. DISCUSSION

4.1 The source of the 'average minimum depth of 0.5 m of peat'

Perhaps the most curious feature about the concept of 'a 0.5 m average minimum depth of peat' is its origins. It is worth re-capping the history of recommendations concerning residual depths of peat, if only to highlight the anomalous nature of this concept.

4.1.1 Early guidance about residual peat depth

As explored in Section 3.5.2.1 earlier, some of the earliest discussions about residual peat depth occurred in the 1970's and 1980's. In particular, as reiterated from earlier in the present review, Eggelsmann (1982) specifically recommended that [translated from the original German]:

- no ditch should cut into the sub-soil; and that
- the black (humified) peat layer should everywhere have a minimum thickness of 0.5 m, and a bigger thickness is advantageous. [present author emphasis]

This principle was taken forward by Blankenburg and Kuntz (1987) who re-iterated that, from the point of view of seepage losses alone, their hydrological model indicated that a minimum depth of 0.5 m of low-permeability, strongly-humified peat is required to keep downward seepage to acceptable levels and in order to minimise the effect of cracking. They also assumed that a layer of 'top-spit' [*Bunkerde*] would be placed over the bare peat surface to reduce evaporation and thus the likelihood of the peat cracking. Schouwenaars (1993a) then re-stated and refined these recommendations, particularly observing that a minimum depth of 0.5 m was only acceptable if the peat was H7 or more, but if the peat was less than H7 the required minimum residual depth might need to be 1 m or more.

Tüxen (1988), on the other hand, has argued that generic guidance cannot be given because every site is different and that every site should therefore be subject to detailed survey before deciding an appropriate depth of residual peat. From the evidence assembled for purposes of the present review, there is much value in what Tüxen (1988) says, particularly in the light of the site-evaluation exercises carried out by Morgan-Jones *et al.* (2005) on a range of UK raised bogs.

4.1.2 Later UK guidance about residual peat depth

In their review of restoration measures for cut-over bogs, undertaken for the Department of the Environment, the guidance from Eggelsmann, Blankenburg and Kuntz, and Schouwenaars, is repeated by Wheeler and Shaw (1995) in two places – their Sections 4.4.5 and 6.5.3. In the latter section, Wheeler and Shaw (1995) make explicit reference to the difference between an *average* depth and a *minimum* depth (their emphasis).

Wheeler and Shaw (1995) also echo Eggelsmann's recommendation that no ditch should cut into the sub-soil by noting [their Section 6.5.3] that drains should not be dug into mineral subsoil (unless the subsoil is impermeable). They additionally note that this may be impossible to achieve if an *average* depth of 0.5 m is retained.

The Report of the Working Group on Peat Extraction and Related Matters (Department of Environment, 1994), which pre-dated publication of the final Wheeler and Shaw (1995) report, drew on a draft version of that report to recommend that (para 214):

> *"The retention of residual ombrotrophic peat is important if a raised bog vegetation type is to redevelop. A critical depth has not been established, but some work indicates that as a general rule a depth of around 50 cm of peat*

left in situ may be sufficient when the residual peat is low permeability black peat, although on sites overlying impermeable strata the residual depth may be less significant. In practice the depth of residual peat will need to be based on site specific considerations."

The Working Group also re-emphasises (para 219, vii) that drains should not be dug into the mineral subsoil (unless it is impermeable).

In their subsequent review of restoration requirements for cut-over bogs, Money and Wheeler (1999) state that they believe there to be: *"...little reason to presume that the acidic, low nutrient environment of ombrotrophic surfaces is necessary, or even optimal, for the growth of Sphagnum species..."* They present no clear or tested evidence to support this statement, however, so it is difficult either to make a critical assessment of their statement nor judge the rigour with which such conclusions have been arrived at.

The fact that almost every restoration action described for industrially cut-over bogs in the UK and abroad has resulted in a poor-fen community, and the fact that neither Wheeler and Shaw (1995) nor Money and Wheeler (1999) can point to a successful example of ombrotrophic bog restoration (as opposed to poor fen) on industrially mined sites, suggests that a thickness of peat – ombrotrophic peat – may indeed be important.

4.1.3 Recent international recommendations

In their restoration guidelines for the Canadian peat industry, Quinty and Rochefort (2003) state that although no threshold has been determined [at that time] for residual depths of peat, they recommend that <u>at least</u> 50 cm should be left in situ [present author emphasis]. They also observe that a layer of strongly-decomposed peat poses significant challenges for *Sphagnum* establishment because it is difficult to maintain the required levels of water table and pore-water pressure with such peat. They also strongly emphasise the fact that: *"When doing any type of work, it is important* ***not to reach the mineral substrate****."* [their emphasis], echoing the similar earlier recommendations of many authors.

The recent results of a 10-year restoration programme at Bois des Bel, Quebec, suggest that this site is now well on the way to developing an ombrotrophic bog vegetation, although it currently still also supports a range of fen species. McCarter and Price (2013) suggest that once the water table in the newly-formed *Sphagnum* layer combines with the water table in the original cut-over layer, the bog environment will become established – though they cannot give a timescale for this. It will be interesting to see whether this transition finally results in replacement of the fen species with true bog species. The key point about this site is that it has a residual peat depth of less than 2 m and thus it is possible – even likely – that the vascular plant community is still rooting in the basal fen peat and is thus influenced by the mineral content of that peat.

More recently still, the extensive survey of industrially cut-over sites undertaken in Estonia by Triisberg *et al.* (2014) indicates that 2.3 m may represent a critical residual peat depth. On the basis of their results they recommend that a restoration programme which seeks to re-establish ombrotrophic bog vegetation directly requires a minimum residual peat depth of 2.3 m, while any site with a thinner residual peat depth is likely to show fenland characteristics. Consequently restoration programme for such sites will most likely need to re-establish peat-forming conditions through some form of fen rather than bog vegetation.

Practical application of this Estonian recommendation has been demonstrated by Karofeld *et al.* (2015), who have begun successful re-establishment of an ombrotrophic *Sphagnum* sward on a milled peat surface which has approximately 2.5 m of residual peat, the uppermost part of which is ombrotrophic peat.

4.2 Justification for the 'average minimum depth of 0.5 m of peat'

What is quite clear in the whole chronology of recommendations and advice outlined above is that there has *never* been an official or scientific recommendation to adopt the principle of an 'average minimum depth'. Indeed Wheeler and Shaw (1995) explicitly highlight the *difference* between an average depth and a minimum depth. The origins of the concept are thus extremely obscure. It appears to have no underlying scientific support or justification and to have sprung fully-formed, like Aphrodite, from a somewhat nebulous genesis.

Furthermore the apparent practical application of such a principle as part of existing or proposed planning consents makes it clear that many areas will have much less than 0.5 m of residual peat at cessation of working. Indeed some areas may be left with no peat at all. Meanwhile the origins, not to say the guidance, for practical application of the principle are, like the principle itself, very obscure.

5. CONCLUSIONS

The principle of 'an average minimum depth of 0.5 m residual peat' has no basis in scientific evidence nor in official planning guidance.

Scientific evidence is consistent in requiring a minimum residual peat depth of 0.5 m, but only provided the peat is strongly humified (at least von Post H7) *and* covered with 'top-spit' material to prevent drying and cracking of the peat. If the peat is less humified or otherwise permits more rapid water seepage, the residual peat layer must be at least 1 m thick.

Such recommendations will not ensure the development of ombrotrophic bog vegetation. It is almost certain that a poor-fen vegetation will develop, at least initially, because the lowermost 2 m of a lowland raised bog peat is likely to consist of fen peat rather than ombrotrophic bog peat.

If fen vegetation develops instead of bog vegetation, it appears that many decades – and possibly a century or more – will pass before the vegetation transitions to that characteristic of an ombrotrophic bog.

The most recent research, backed by practical experimentation, recommends that a residual peat layer of at least 2.3 m must remain if an ombrotrophic bog vegetation is to be restored directly.

As to whether fen restoration is an acceptable restoration after-use for commercial peat extraction sites, Triisberg *et al.* (2014) have this to say:

> *"Considering that (1) peat extraction areas are largely created in raised bogs and, (2) the raised bogs provide valuable service as fresh water reservoirs and carbon sinks (Keddy, 2010), the main target of restoration should be directing the re-vegetation succession toward raised bogs."*

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ANNEX 1: NUMBERS OF DATABASE HITS FOR SEARCH PHRASES

The table below gives the total number of hits obtained from the key electronic databases using defined search terms. Many of these hits will represent hits for the same papers identified using differing search phrases.

	Number of hits			
Search Phrase	**Google Scholar**	**Open Access**	**Science Direct**	**Scopus**
Peat Depth AND Restoration	41,600	7	2,088	91
Peat Depth AND Sphagnum restoration	12,000	0	346	18
Remaining Peat AND vegetation	73,400	6	14,313	63
Bog Restoration AND Residual Peat	9,400	0	248	6
Underlying peat AND restoration	25,400	1	1,202	2
Peat Depth AND Restoration	41,600	7	2,088	91
Peat depth AND vegetation	137,000	33	12,358	522
Residual peat depth AND Bog Vegetation	14,800	0	1,074	5
Peat depth FOR Bog Vegetation	53,100	10	4,612	137
Peat Depth AND Sphagnum restoration	12,000	0	346	18
Recovery AND sphagnum harvest	14,300	0	402	2
Peat depth AND vegetation recovery	37,800	0	3,133	17
peat depth, raised bog, recovery, vegetation, harvest	8,740	0	176	0
Bog AND restoration	31,500	25	1,928	336
raised bog AND UK AND development	25,500	0	1,681	0
Ombrotrophic peat depth AND restoration	2,320	0	136	4
Fen AND raised bog succession	7,910	2	480	21
sphagnum colonization AND peat depth	11,000	0	455	5
fen peat And bog peat	24,200	18	2,068	544
Totals	**583,570**	**109**	**49,134**	**1,882**

ANNEX 2: PAPERS ASSESSED FOR SUB-QUESTION 1

The following papers were selected for detailed assessment in relation to Sub-Question 1: Depth of fen peat.

Sub-Question 1 : Fen-peat depth				
Authors	**Year**	**Category**	**Score**	**Comments**
Bartley *et al.*	1990	3	+++	Depth provided
Clymo	1983	3	+++	Figure 4.12
Gorham	1949	3	+++	Depth provided
Hughes and Barber	2003	3	+++	Figure 2
Hughes and Barber	2004	3	+++	Table 2
Hughes *et al.*	2000	3	+++	Figure 3
Karofeld *et al.*	2015	3	+++	Depth provided
Kivimäki *et al.*	2008	3	+++	Depth provided
Lode and Ilomets	1998	3	+++	Depth provided
Loisel and Yu	2013	3	+++	Average of four sites
Mallory and Price	2014	3	+++	Depth provided
Moore and Bellamy	1974	3	+++	p.147
Ruuhijärvi	1983	3	+++	Figure 2.4B
Rydin and Jeglum	2006	3	+++	Figure 7.5
Sliva *et al.*	1997	3	+++	Figure 32.4
Succow and Jeschke	1990	3	+++	p.66
Tansley	1939	3	+++	Table XXI
Tansley	1939	3	+++	Table XXII
Turner	1970	3	+++	p.101
Wheeler and Shaw	1995	3	+++	Figure 1.1B
Wheeler and Shaw	1995	3	+++	Figure 1.1C
Wheeler and Shaw	1995	3	+++	Figure 1.1D
Wind-Mulder *et al.*	1996	3	+++	Four sites described, with three having surface in fen peat and depth range given; average of *minimum depth* for these three used.

ANNEX 3: PAPERS ASSESSED FOR SUB-QUESTION 2

The following papers were selected for detailed assessment in relation to Sub-Question 2: Peat depth and water chemistry.

Sub-Question 2 : Peat depth and water chemistry				
Authors	**Year**	**Category**	**Score**	**Comments**
Gorham	1949	3	+++	Measured values of pH and conductivity from peat core
Wilhelm *et al.*	2015	3	+++	pH and conductivity measurements in poor-fen site with 3.9 m residual peat
Sliva *et al.*	1997	3	+++	pH and conductivity values for milled site with peat depths
Sliva and Pfadenhauer	1999	3	+++	pH and conductivity values for milled site with peat depth
Konvalinkova and Prach	2014	3	+++	pH and conductivities with peat depths for milled sites
Money	1994	3	+++	Measured values for cations and pH from milled fields
Gonzáles *et al.*	2014	3	+++	Measured values for pH and conductivity in block-cut site
Girard *et al.*	2002	3	+++	Measured values for pH and conductivity in block-cut site
Wind-Mulder *et al.*	1996	3	+++	Measured values for pH and conductivity for milled and block-cut sites
Poulin *et al.*	2005	3	+++	Measured values for pH and conductivity for a wide range of milled and block-cut sites
Malloy and Price	2014	3	+++	Measured values for pH and peat depth
Langlois *et al.*	2015	3	+	Measured chemistry of lagg fen and rand, but no direct measurement of peat depth
Smolders *et al.*	2003	3	+	Measured values for pH on abandoned cut-over sites, but no peat depths
Money	1995	3	+	Chemistry data but an apparent 1.5 m cut-off for peat depth measurements
Maas and Poschlod	1991	2	++	Peat depth with broad chemical fators, plus pH but no peat depths
Tuittila *et al.*	2000	2	++	Peat depths but only chemistry of water entering from other parts of milled site
Poulin *et al.*	2013	2	++	Measured pH values, but peat depth given by other authors
Wheeler and Shaw	1995	2	++	Extensive review but only add a small amount of 'unpublished data'
Quinty and Rochefort	2003	2	+	Review of 'state of the art', with recommended chemical thresholds
Gorham and Rochefort	2003	1	+	Review, but with no supporting data

ANNEX 4: PAPERS ASSESSED FOR SUB-QUESTION 3

The following papers were selected for detailed assessment in relation to Sub-Question 3: Peat depth and hydrology.

Sub-Question 3 : Peat depth and hydrology				
Authors	**Year**	**Category**	**Score**	**Comments**
Baird *et al.*	in press	3	+++	Measured values of catotelm humufication and conductivity
Baird *et al.*	2008	3	+++	Measured values of hydraulic conductivity
Slater	1972	3	+++	Measured thickness of differing layers
Schouwenaars	1993b	3	+++	Review but with significant quantity of original field data
Smolders *et al.*	2003	3	+++	Measured values of hydraulic conductivity
Morgan-Jones *et al.*	2005	3	+++	Measured behaviour of catotelm
Lindsay and Bragg	2004	3	+++	Field evidence for cracking, combined with review
Hughes	2000	3	+++	Field evidence for cracks
Graham and Hicks	1980	3	+++	Measured shrinkage of peat
Sliva and Pfadenhauer	1999	3	+++	Field evidence of conductive peat at base
Hughes and Barber	2003	3	+++	Presence of E.vaginatum peat
Hughes and Barber	2004	3	+++	Presence of E.vaginatum peat
Morgan-Jones *et al.*	2005	3	+++	Field evidence of basal layers
Anderson *et al.*	2000	3	+++	Bad a Cheo subsidence
McCarter and Price	2013	3	+++	Measured field data for w/t in restored Sphagnum surface and underlying residual peat
Poulin *et al.*	2005	3	+++	Measured field data for w/t in milled and block-cut sites
Girard *et al.*	2002	3	+++	Measured field data for w/t in block-cut sites
Konvalinkova and Prach	2014	3	+++	Measured field data for w/t in milled sites
Price *et al.*	1998	3	+++	Measured field data for w/t in flat block-cut area
Karofeld *et al.*	2015	3	+++	Measured field data for w/t in milled site
van der Schaaf	2000	3	+++	Measured and modelled w/t behaviour in drained catotelm peat
Eggelsmann and Klose	1982	3	+++	Restoration response and w/t behaviour on residual depths of 0.8 m+
Pyatt *et al.*	1987	3	++	Review of cracking, with some field evidence
Kleimeier *et al.*	2014	3	++	Recorded evidence of cracks
Roger Meade Associates/Maslen	2008	3	++	Examples of varied site-based hydrological requirements
Stephenson *et al.*	1988	3	++	Review - typical examples of hydraulic condictivities for soils
Blankenburg and Kuntze	1987	2	+++	Review and modelling - for seepage, at least 0.5 m necessary + Bunkerde; cracking if <0.5 m.
Eggelsmann	1980	2	+++	Review of water bodies
Eggelsmann	1987	2	+++	Extensive review - residual depth >0.5 m; Bunkerde is important; 1 m+ needed for bog hollows
Ingram	1983	2	+++	Review, with range of supporting data
Ryecroft *et al.*	1975	2	+++	Review of humification and water movement with measured values from others

Clymo	1983	2	+++	Review, with range of supporting data
Schouwenaars	1993a	2	+++	Review, with threshold values and some supporting data
Hobbs	1986	2	+++	Review - with examples of typical field data for shrinkage
Blankenburg	2004	2	+++	Review, with clear evidence of cracking
Eggelsmann	1975	2	+++	Review, with typical example measurements of subsidence
Lindsay	2010	2	+++	Review of w/t behaviour, with field data
Price *et al.*	2003	2	+++	Review of water-table behaviour in cut-over sites, with values taken from own work
Wheeler and Shaw	1995	2	++	Review, with supporting data from others for humification
Quinty and Rochefort	2003	2	++	Review of restoration hydrology, with detailed thresholds but no supporting data
Joosten	1995	2	+	Review, with process described but no relevant supporting data
Gorham and Rochefort	2003	2	+	Review of water table requirements for restoration, thresholds but no supporting data
Eggelsmann	1982	1	++	Review gives threshold values
Kuntze and Eggelsmann	1982	1	+	Review, but with no supporting data

ANNEX 5: PAPERS ASSESSED FOR SUB-QUESTION 4

The following papers were selected for detailed assessment in relation to Sub-Question 4: Peat depth and vegetation

Sub-Question 4 : Peat depth and vegetation				
Authors	**Year**	**Category**	**Score**	**Comments**
Paradis *et al.*	2015	3	+++	Measured link between peat depth and vegetation
Artz *et al.*	2008	3	+++	Measured link between peat depth and vegetation
Money	1994	3	+++	Measured link between peat depth and vegetation
Tuittila *et al.*	2000	3	+++	Measured link between peat depth and vegetation
Poulin et al	2013	3	+++	Measured link between peat depth and vegetation
Malloy and Price	2014	3	+++	Measured link between peat depth and vegetation
Konvalinkova and Prach	2014	3	+++	Measured link between peat depth and vegetation
Girard *et al.*	2002	3	+++	Measured link between peat depth and vegetation in block-cut and milled site
Gonzáles *et al.*	2014	3	+++	Measured link between peat depth and vegetation in block-cut site
Poulin *et al.*	2005	3	+++	Measured link between peat depth and vegetation
Taylor and Price	2015	3	+++	Measured link between peat depth and vegetation
Triisberg *et al.*	2014	3	+++	Measured link between peat depth and vegetation
Money	1994	3	+++	Measured link between restoration of bog Sphagnum and water quality/peat depth
Money	1995	3	+++	Measured link between Sphagnum establishment and indicative peat depth
Sliva and Pfadenhauer	1999	3	+++	Measured response of vegetation on site with known peat depth
Karofeld *et al.*	2015	3	+++	Measured response of vegetation on site with known peat depth
Price *et al.*	1998	3	+++	Measured response of vegetation on site with known peat depth
McCarter and Price	2013	3	+++	Measured response of vegetation on site with known peat depth
Meade	1992	3	++	Survey of restoration site, but no peat depth data
Meade	2003	3	++	Survey of restoration site, but no peat depth data
McMullen *et al.*	2004	3	++	Survey of restoration site, but no peat depth data
Kivimäki *et al.*	2008	3	++	Vegetation description but no peat depth - given in earlier papers
Sliva *et al.*	1997	3	++	Vegetation response on milled site, with peat depth given in earlier papers
Meade	2003	3	++	Measured response of Sphagnum transplants but no peat depth data
Sliva *et al.*	1997	3	++	Measured responses of vegetation - in site of known peat depth
Poschlod *et al.*	2007	3	++	Review - with field data for sites of know peat depth
Wheeler and Shaw	1995	3	+	Survey of restoration sites, but no peat-depths or vegetation composition
Maas and Poschlod	1991	3	+	Review - with summarised field data for vegetation response
Schouwenaars	1993b	2	+++	Review - with significant field data
Maas and Poschlod	1991	2	+++	Review of restoration response, with

				some field data
Vasander and Roderfeld	1996	2	++	Review of restoration site, with some field data
Wheeler and Shaw	1995	2	++	Review - unclear link between vegetation and peat depth
D'Astous *et al.*	2013	2	+	Incidental description of vegetation as fen on site
Quinty and Rochefort	2003	2	+	Review - identify specific thresholds for depth and vegetation targets

ANNEX 6: PAPERS ASSESSED FOR SUB-QUESTION 5

The following papers were selected for detailed assessment in relation to Sub-Question 5: Timescale of transition from poor fen to ombrotrophic bog.

Sub-Question 5 : Timescale of transition from poor fen to bog				
Authors	**Year**	**Category**	**Score**	**Comments**
Hughes *et al.*	2000	3	+++	Measured field data
Hughes and Barber	2003	3	+++	Measured field data
Hughes and Barber	2004	3	+++	Measured field data
Lucchese *et al.*	2010	3	+++	Measured field data
McCarter and Price	2013	3	+++	Measured field data
Karofeld *et al.*	2015	3	+++	Measured field data
Artz *et al.*	2008	3	++	Measured field data but no detailed vegetation data
Wheeler and Shaw	1995	3	++	Measured field data with no detailed vegetation data
Walker	1970	2	+++	Review - with measured examples
Joosten	1995	2	+++	Review - with field data presented
Money and Wheeler	1999	2	++	Review - limited supporting field data cited
Gorham and Rochefort	2003	2	++	Review - suggested timescales based on limited data

ANNEX 7: PAPERS ASSESSED FOR SUB-QUESTION 6

The following papers were selected for detailed assessment in relation to Sub-Question 6: Consequences of using an average minimum residual peat depth of 0.5 m.

Sub-Question 6 : Potential effects of average minimum of 0.5 m residual peat depth				
Authors	**Year**	**Category**	**Score**	**Comments**
Wheeler and Shaw	1995	3	+++	Profile of basal sediments
Gore	1983	3	+++	Profile of basal sediments
Taylor	1983	3	+++	Profile of basal sediments
Botch and Masing	1983	3	+++	Profile of basal sediments
Sliva *et al.*	1997	3	+++	Profile of basal sediments
Rydin and Jeglum	2006	3	+++	Profile of basal sediments
Graham and Hicks	1980	3	+++	Measured shrinkage with drying
Morgan-Jones *et al.*	2005	3	+++	Surveyed nature of sub-soil
Sliva and Pfadenhauer	1999	3	+++	Eriophorum in basal sediments
Karofeld *et al.*	2015	3	+++	Stripping of surface required - so further reducing thickness
Taylor and Price	2015	3	+++	Water table fluctuations
McCarter and Price	2013	3	+++	Water table fluctuations
Money	1994	3	+++	Review of restoration sites
Eggelsmann and Klose	1982	3	++	Summary data for restoration site - value of Bunkerde in controlling w/t
Pyatt *et al.*	1987	3	++	Cracking
Vasander and Roderfeld	1996	3	+	Observation that mineral base exposed
Price *et al.*	2003	2	+++	Water table fluctuations
Blankenburg	2004	2	++	Absence of covering vegetation leads to cracking
Schouwenaars	1993a	2	++	Review - potential consequences hydrologically, sub-soil, and cracking, plus Bunkerde
Hobbs	1986	2	++	Subsidence
Eggelsmann	1987	2	++	Review - value of Bunkerde
Blankenburg and Kuntze	1987	2	++	Review and modelling - seepage losses unchanged with >0.5m - value of Bunkerde avoiding cracks
Money and Wheeler	1999	2	+	Review - suggest that ombrotrophic peat, indeed any thickness of peat, is not critical
Eggelsmann	1982	2	+	Review - criteria for residual peat thickness and expectation of Bunkerde

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ISBN: 978-1-78391-398-5

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