Appendix A. Literature review (completed April 2010) and systematic review (completed July 2014).

Investigation of Peatland Restoration (Grip Blocking) Techniques to Achieve Best Outcomes for Methane and Greenhouse Gas Emissions / Balance: Literature Review

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Defra project SP1202

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1. Purpose and the literature base

The purpose of this review is to bring up to date the final report on Defra project SP0574 (**Baird *et al*., 2009**). In particular, the aim is to provide (a) the latest information on grip blocking techniques used in the UK, and (b) the latest information on what is known about methane (CH_4) emissions from restored peatlands, especially blanket peatlands. It was noted at the Defra SP1202 Inception Meeting of 1st March 2010 that (a) and (b) will be of particular use in finalising the design of the mesocosm experiments; they will also inform the design of the field trials.

Since **Baird *et al*. (2009)** was produced, a number of other detailed reviews have appeared, notably:

Bussell, J., **Jones**, D.L., **Healey**, J.R., and **Pullin**, A. 2010. *How do Draining and Re-wetting Affect Carbon Stores and Greenhouse Gas Fluxes in Peat Soils?* CEE review 08-012 (SR49). Collaboration for Environmental Evidence: www.environmentalevidence.org/SR49.html.

Couwenberg, J. 2009. *Methane Emissions from Peat Soils (Organic Soils, Histosols): Facts, MRV-ability, Emission Factors*, Wetlands International, Wageningen, 16 pp.

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*. RSPB Scotland with funding support from Scottish Natural Heritage, Countryside Council for Wales, Natural England and the Forestry Commission, 315 pp.

To some extent, all of these cover similar ground to **Baird *et al*. (2009)**; however, all contain useful additional information on CH_4 emissions from, and carbon-balance processes within, restored peatlands, and their findings are discussed in the succeeding sections.

In addition to the listed reports, we also read the following:

Schils, R., **Kuikman**, P., **Liski**, J., **van Oijen**, M., **Smith**, P., **Webb**, J., **Alm**, J., **Somogyi**, Z., **van den Akker**, J., **Billett**, M., **Emmett**, B., **Evans**, C., **Lindner**, M., **Palosuo**, T., **Bellamy**, P., **Jandl**, R., and **Hiederer**, R. 2007. *Review of Existing Information on the Interrelations between Soil and Climate Change*. ClimSoil Final Report on Project 070307/2007/486157/SER/B1, Wageningen, 208 pp.

Schils *et al*. (2007) considers a wide range of soil types and has relatively little information on peats. However, it did provide one useful additional reference on carbon (C) sequestration by restored peatlands (i.e., **Yli Petäys *et al*., 2007**) and provides a good summary of grazing effects on peatland C-balance processes. The latter is discussed in section 3.4.

Some recent academic papers on CH_4 dynamics in peat soils prior to and after restoration have also been published, while some additional older academic papers have been found through further literature searches. Where appropriate, the findings of these papers are reported below.

2. Grip blocking methods and materials

Grip blocking methods were reviewed in **Baird *et al*. (2009)**, who noted (pp. 12-13):

> "Drain-blocking is a very common practice in peat restoration projects. Significant investment on drain blocking is taking place in both the UK uplands (where it is called grip-blocking) and on lowland raised bog and fen sites. The first upland peat drain dams in the UK were installed in Caithness, Scotland, in the late 1980s, and there has been a dramatic increase in blocking during the last five years throughout the UK. A mixture of techniques have been used, including the creation of dams using peat turves, plastic piles, wooden planks and plywood, heather bales, straw bales and stone.

"A recent survey of UK upland drain-blocking techniques is provided by **Armstrong *et al*. (2009)** who surveyed 32 drain-blocked sites across the UK and interviewed all of the key stakeholders. The distribution of some of the block types was found to be regional: corrugated Perspex was predominantly used in Scotland and plywood dams mainly at sites surrounding Kielder Water and on Exmoor. A style of drain-blocking involving peat turves was generally preferred by practitioners and was also the most cost-effective: 74% of surveyed drains/grips had been blocked using this method. The technique was usually successful except where there are steep slopes, where there is severe erosion, in very wet or very dry locations, or if the mineral substrate is exposed. Escape routes that encourage water flowing over and around dams to seep across the peat mass, rather than around the dam and back into the drain downslope, were noted as desirable design features by **Armstrong *et al*. (2009)**, but were often not included at both the design and build phases. If peat turves are to be used for drain blocking, it was recommended that they be taken from upstream of the dam such that a shallow pool is created after dam construction. If pools are too deep there is evidence that revegetation will not be as efficient (**Armstrong *et al*., 2008**); overhanging vegetation also inhibits revegetation within the drain pools. On the other hand, some landowners see the pools as useful because they increase the area of standing water for grouse to drink from and provide habitat for invertebrates that grouse feed on."

We were unable to find any published information that was more up-to-date than that provided in **Baird *et al*. (2009)**, who in turn used information provided by Defra project SP0556 (*A Compendium of Peat Restoration and Management Projects* – see **Walker *et al*., 2008**) and in **Armstrong *et al*. (2009)**. However, it is worth adding some detail to what was written by **Baird *et al*. (2009)**. As the quoted passages above show, **Baird *et al*. (2009)** described mainly how grips may be dammed. Grips may also be filled in, and it was found when preparing the bid for this project (SP1202) that it is common in some restoration projects to block ditches throughout their entire length with tree slash (small branches, twigs and waste produced from tree felling) and with heather bales. Discussions with the National Trust, both during the preparation of the bid for SP1202 and after the award was made, also make clear that the creation of open water is not always popular with farmers and landowners (Trystan Edwards[1] pers. comm.). For example, in the Migneint (Upper Conwy, North Wales), there is concern that grips blocked with dams in which the lengths between the dams are left with open water could pose a hazard to livestock (sheep may become trapped in these, especially if the blocked ditches are partly obscured by over-hanging vegetation or vegetation rafts). It is also clear that blocking grips throughout their entire length with peat is being seen as an increasingly attractive restoration option by the National Trust. It seems that this method of blocking uses peat from either side of the grip and results in a slightly depressed area along the course of the former grip. In essence it is a method of partial infilling and re-profiling of the grip and part of the peatland either side of it.

Lindsay (2010) briefly reviews grip blocking methods. He makes the following observations on the blocking of grips with peat (p. 153):

"Sometimes the option exists to roll back into the drain the ridge of peat turf dug to make the drain in the first place. Given that peat shrinkage can be considerable in the first few months after drainage, the peat turf itself is likely to have shrunk by a substantial degree unless it can be turned back within a month or two of having been dug.

"More usually, this turf has been lying on the bog surface for some years and has thus had much time to shrink and oxidise. That said, the drain itself may well have shrunk and slumped if it has not been maintained during the intervening years. Braekke (1983) found that some drains cut in soft peat had shrunk from between 30 cm – 1.1 m deep to only 18 cm - 29 cm deep in 10 years.

"Nevertheless, it can usually be assumed that a turf turned back into a drain will no longer fill that drain. If this is the chosen restoration strategy, it is likely that the drain will remain as a shallower furrow. The somewhat

[1] Trystan Edwards is the National Trust's Farm and Countryside Adviser for Wales and Project Manager of the Trust's Upper Conwy Catchment Improvement Project.

undulating nature of the turned-back turf will reduce the ability of this furrow to convey water away quickly, and may well tend to encourage paludification of both this surface and the furrow sides. It is unlikely that terrestrialisation would feature prominently in such a scenario unless dams were added as well."

Lindsay's (2010) description of grip infilling differs somewhat from the grip re-profiling method described above, where fresh peat (not old turf left over from past ditch construction), is used to partially infill the grip. The terms 'paludification' and 'terrestrialisation' may also require some explanation. Both terms have a specific meaning in wetland science as follows (quoted from **Rydin and Jeglum (2006)**):

"*Paludification* is a term meaning the development of peatland over previously less wet mineral ground." (p. 124).

"*Infilling* is the process whereby peat develops on the margins and in the shallow waters of ponds, lakes, or slow-flowing rivers. An often used term is *terrestrialization* (Weber, 1902), but the resulting ecosystem can be far from 'terrestrial', and therefore we prefer the term infilling." (p. 122).

Lindsay (2010) uses the terms somewhat differently. He uses 'paludification' to describe the increasing wetness of inter-grip areas after grip blocking or infilling (as the water table in these areas rises). 'Terrestrialisation' is used (by him) to describe the colonisation of open water behind a grip dam with aquatic Sphagna and also the 'rafting over' of such areas of open water by Sphagna (and sometimes cotton grasses – the Eriophora).

Finally, it is worth noting that **Lindsay (2010)** makes a distinction between grip dams proper and filters. He places heather bales in the latter category and suggests (p. 153):

"Heather bales are not designed to act as impermeable barriers which will pond water behind them. They instead function as filters which trap peat sediment and thereby encourage the drain to choke up and infill with this loose material."

3. Changes in vegetation composition and carbon balance processes after restoration

3.1. The need for further work, and changes in vegetation composition and carbon gas fluxes post-restoration

Perhaps the most significant piece of work to have been published since **Baird *et al*. (2009)** is **Lindsay's (2010)** detailed review (315 pages). On the whole, **Lindsay's (2010)** report is a thorough and readable summary of research on C-balance processes in peatlands. It puts key findings into a UK context and complements the literature review of **Baird *et al*. (2009)**; indeed, it is recommended that it is read alongside **Baird *et al*. (2009)**. In the context of the current Defra project (SP1202), the following points from Lindsay's executive summary are interesting and worthy of further comment (the points follow Lindsay's numbering scheme and are quoted verbatim):

"11. Evidence suggests that methane arising from the action of bacterial [*sic* – methane is produced by archaea] decomposition in the catotelm may remain largely locked up in the peat under natural conditions, contributing to the low conductivity [hydraulic conductivity or permeability] of this lower peat. In the acrotelm, methane is both produced and oxidised by different microbial populations. Different microtopographical surface features (e.g. hummocks, pools) and different vegetation types all show differing methane emissions." [square brackets denote additions]

"12. Sphagnum-dominated swards can suppress methane through oxidation. In contrast, some vascular plants growing in bog pools and hollows can act as routes for direct methane release, transferring methane from lower levels to the atmosphere directly, thus by-passing the oxidising layer in the acrotelm. There have been relatively few long term methane studies on undamaged natural UK peatlands. There have been even fewer studies which take explicit account of the relationship between emission levels, vegetation, and associated hydromorphological structures (e.g. pools, carpets, hummocks)."

"31. Methane emissions on drained peatlands fluctuate considerably over a year, with annual totals often much smaller than indicated by peak amounts. Results from short-term studies must therefore be treated with caution. There are few long-term studies of methane and drains in UK peatbogs."

"37. Methane emissions associated with restoration may thus be relatively short lived (perhaps less than 5-10 years) and of course they are localised within the ditches. There is evidence to suggest that in both ditches and the wider bog surface, re-establishment of *Sphagnum* can suppress methane emissions arising from the peat. *Sphagnum* dominance in the ditches also reduces the vigour and abundance of vascular plants responsible for methane transport."

"38. The amounts of methane released from re-wetting are likely to be low in relation to the overall carbon and global warming benefits of restoration. Indeed the limited amount of existing evidence from re-flooded peat bog systems suggests that methane emissions, though showing an increase compared to the drained state, are still lower than those found on natural peatbog systems. In addition, such emissions must be balanced against the long-term losses of carbon dioxide which would have occurred had the site not been brought into conservation management."

It is clear that **Lindsay (2010)** recognises the dearth of work on CH_4 emissions from UK peat bogs, and that further work is needed and should take a long-term perspective. His recommendation for more work perhaps comes across most strongly in Appendix 1 of his report where he notes (p. 280):

"During the course of the present review, what has become evident is that figures for the carbon balance of peatland systems in Britain are based on a remarkably small number of research studies and an even smaller number of research sites. Given that some of these have, in addition, not been adequately described or characterised, the whole basis of carbon-budgeting for peatlands in Britain (and probably Ireland) at present appears to resemble an inverted pyramid balanced on a remarkably small plinth."

As such, his comments can be regarded as an endorsement of the long-term approach being taken with the current Defra project (SP1202). Nevertheless, he identifies 5-10 years as being something of a defining boundary when considering the effects of peatland restoration on CH_4 emissions. He suggests that, in the early stages after restoration, CH_4 emissions from bogs may be quite high, especially if the vegetation is dominated by sedges (i.e., the cotton grasses – *Eriophora*), but that this initial stage might be short-lived, with CH_4 emissions dropping as *Sphagnum* re-establishes (refer to section 10.2.1 *Gaseous carbon responses to drain blocking – CO_2 and CH_4*, p. 156 of **Lindsay (2010)**). A similar conclusion has been reached by **Augustin and Joosten (2007)** in the context of restored peatlands more generally. The latter article was not included in the review for Defra project SP5074 (**Baird *et al*., 2009**) because it is more of an opinion piece and appears to lack a sound empirical basis. Although it is quite possible for the stages described by **Lindsay (2010)** to occur, we have some concern that there is little information on plant successional changes in peatlands post-restoration. Email correspondence between Andy Baird and Richard Lindsay about the vegetation trajectories after restoration helps clarify what is known. In an email to Andy Baird on 6th April 2010, Richard Lindsay confirms that he would expect *Sphagnum* cover to increase after restoration. Relevant parts of his email are reproduced below:

"I'd also been meaning to contact you about your very valuable methane review. I'd already mentioned to Joe Holden that there are aspects I'd like to pursue further. I guess the key point I would emphasise but which doesn't come out of your review is the response of the vegetation to restoration. Your report leaves the story after Act 2, as it were, and doesn't mention the possibility/probability that there is an Act 3 where Sphagnum has the potential to smother areas of open water with a high effective methane-oxidising layer. The absence of bog bean from most of the Pennines also means that the methane-shunt mechanism is largely attributed to 'sedges'. While botamcially correct to describe cotton grass and deer grass as sedges, perversely most peatland ecologists would restrict the term 'sedges' to members of the genus 'Carex' - which undoubtedly do act as methane shunts in more fenland/seepage conditions. However, within Pennine blanket bog the main group of such plants would be cotton grasses, and these would be described as cotton grasses rather than sedges. I guess what I'm saying is that there is the potential for confusion in the use of the term 'sedge', raising the question of whether the dangers of methane-release you highlight relate to Carex-dominated minerotrophic (fen) parts of the blanket mire landscape only, or whether you actually mean the ombrotrophic cotton-grass bogs. I know you name the species in places, but there is still the potential for ambiguity.

"The point about the cotton grasses is that the vigour of both is reduced as the Sphagnum sward becomes established and asserts itself. Common cotton grass will grow fairly vigorously through a Sphagnum cuspidatum sward as the Sphagnum colonises a drain, but as more 'terrestrial' Sphagnum species such as Sphagnum papillosum, S. magellanicum and S. capillifolium become established over the S. cuspidatum carpet the cotton grass sward becomes much more sparse. Similarly, hare's-tail cotton grass on the peat adjacent to the blocked drain will become much less vigorous as terrestrial Sphangum species establish themselves on wetter peat adjacent to the drain. Sphagnum can colonise and choke dammed drains within 5-10 years (though the timescale in the southern Pennines is an interesting topic for debate). From this point on, one might expect methane emissions steadily to diminish. This is what I would describe as Act 3 - but your review leaves this open, leaving the reader to surmise that areas of open water would remain there indefinitely and thereby pose an indefinite methane problem.

"Please don't get me wrong, I think the review is really excellent and incredibly useful. I just feel that Act 3 is missing...and the one thing which emerged for me from my review was the way that Sphagnum appears time and time again as the key to so many issues. Anyway, my review is described as a 'discussion document', permitting me to speculate and make potentially controversial suggestions, so please feel free to kick my ideas and thoughts around as vigorously as you like - I won't be offended - in fact I would welcome it because hopefully at least a few useful things would eventually emerge from the dust..."

In an email reply of 8th April 2010, Andy Baird wrote (the text in square parentheses has been added here for clarity):

"2. I agree in part with your comment about sedges. I know there is the potential for confusion with fens and Carex spp. In hindsight, we could have done better in our Defra report in making it clear every time we mention sedges that we meant Erophorum spp. and other bog species such as Rhynchospora. However, I am not so sure that all peatland ecologists think of the Eriophora as cotton grasses and not sedges. Lisa [Belyea – Queen Mary University of London], for one (and very much an ecologist), always refers to them as sedges. I guess there is the perennial danger that we all speak different languages or at least different dialects and that we need to take more care in not assuming everyone else is like us. So, I shall certainly be more careful in future when using the words 'sedge' and 'sedges'!

"3. Your point about vegetation establishment and successional changes after restoration is well-made. I agree that our Defra report stopped short of discussing such changes (of Act 3). In part that was because of time constraints. However, it was also because of concerns on my part that the evidence for such successional changes is not strong. In your RSPB review, you talk of reestablishment of Sphagnum after c. five years and how Sphagnum can act to reduce methane emissions. I suppose my concern is that I don't think it is necessarily a given that Sphagnum will re-establish in the way you suggest. Your experience is much much greater than mine, but there are cases where the palaeo-record shows dominance by the Eriophora in our blanket bogs (e.g. on Dartmoor). This suggests to me that the Eriophora can dominate peatland vegetation for long periods. So, is it necessarily the case that the Sphagna will reestablish? Many (relatively) undamaged blanket peatlands also show complex mixtures of 'micro-community' where Eriophora remain abundant. So, I am not convinced that carpets of Sphagnum will establish and cause die back or loss of vigour of the cotton grasses. I would be convinced if I could find reports/papers that show such Sphagnum establishment but you don't seem to cite such publications. Now, you could be drawing on your great wealth of experience and that is not to be dismissed lightly, but are there other lines of evidence I can look at? What I would like to do is draw Defra's attentions to your views and experience because I think we need to recognise that, as an expert, you think the restoration picture is not as bleak as painted by some (including perhaps myself). Would you object to me using your previous email in this way or would you prefer for that to remain confidential?”

Finally, Richard Lindsay responded (also on 8th April) as follows:

“'Sedges' - yes, tricky one, as I also often refer to cotton grasses as sedges. I guess my point is that where one was making the distinction between plants of the Cyperaceae family and examples of the Carex genus, one would then tend to use the word 'sedges' to describe the Carex species in particular.

“Sphagnum recovery - and dominance in peat: well, yes, it does indeed vary depending on conditions, but in general, blocked drains show a fairly rapid Sphagnum response. I've got various examples from around the country, but perhaps it needs more formal pulling together than has been the case to date - Bryan Wheeler's DoE review did some of that, but there's been a great deal more activity since then. As for the evidence of Eriophorum forming significant layers of peat, that's very true. The story of Eriophorum vaginatum and Sphagnum recovery is an interesting one and not one I have time to go into now, but it is clear we could have a useful discussion about our least-favourite ground to walk over - namely 'custard'...

“I'd be very happy for you to forward my e-mail to DEFRA. The more they have to think about the better, and debate can only be a good thing.”

The ‘natural’ replacement of sedges (*Eriophorum* spp. – the cotton grasses) and other vascular plants by *Sphagnum* after grip blocking is perhaps not as certain as originally implied by Lindsay in his 2010 report. There is probably little doubt that many, if not all, grips with dams and open water behind the dams and grips blocked with heather bales or tree slash will see a fairly rapid development of aquatic Sphagna (*Sphagnum cuspidatum* Ehrh. ex Hoffm., and *S. recurvum* P. Beauv. in places). Certainly, many dammed ditches in a variety of circumstances (i.e., ditches in cutover raised bogs as well as in blanket peatlands) do show infilling by aquatic Sphagna and rafting by other species (examples can be found in **Wheeler and Shaw (1995)** as suggested by Lindsay in his email of 8th April 2010 – see above). Given that such infilling and rafting appear to be common, it makes sense to include such a scenario in the mesocosm experiments, and it is recommended that this option is discussed at the first meeting of the Steering Group on 14th April 2010.

It is less certain what will happen in the areas between the grips. There may not necessarily be a rapid spread of terrestrial Sphaga and a dieback or loss of vigour of the cotton grasses. Even though our field trials (on SP1202) will cover a shorter period of time than the long-term monitoring implied by **Lindsay (2010)**, it should be possible to detect changes in *Sphagnum* cover in both the ditches and the inter-grips areas. The uncertainty here means that more emphasis should be given to the vegetation monitoring in the field trials, especially to how the vigour (and not just the cover) of the cotton grasses may be monitored. It would be very useful to discuss the details of such monitoring at the first meeting of the Steering Group on 14th April 2010.

At this point it is worth considering the report by **Bussell *et al*. (2010)**. This report contains a meta-analysis of data on the effects of drainage and rewetting on carbon-balance processes in peatlands. It is interesting that such an analysis has taken place, given the following observation by **Baird *et al*. (2009)** (p. 14):

“Originally, it was hoped that data from the various reviewed studies could be brought together in a meta-analysis so that the effects of, for example, different types of restoration on CH_4 fluxes could be predicted. However, such an intention proved optimistic. Unlike in medical trials, there is wide variability in the aims and approaches used in studies of carbon-balance processes in peatlands, which makes it very difficult to bring data together into a common format. Thus, it was not possible to perform a meta-analysis such as those carried out for medical interventions by the Cochrane Collaboration (www.cochrane.org).”

In view of the reservations of **Baird *et al*. (2009)**, how was such an analysis possible? **Bussell *et al*. (2010)** appear to have followed rigorous statistical protocols both in terms of judging the statistical design of the studies included in their meta-analysis and in the meta-analysis itself. However, if their meta-analysis has a limitation, it is in their criteria for data selection and inclusion. It appears that their criteria do not take account of the accuracy of the methods of measuring carbon gas fluxes between peatlands and the atmosphere. As noted by **Baird *et al*. (2009)**, flux chambers may give inaccurate estimates of ebullition fluxes. There is also wide variation in chamber use, and, unfortunately, most studies do not (and are not required to by journal editors) publish sufficient detail of measurement protocols for data quality to be properly evaluated by readers. Statistical design is very important, but the results from a study can be strongly biased if robust measurement protocols are not followed.

Bussell *et al*. (2010) are rightly critical of the poor statistical design of many projects and note that a common problem is that of repeated measures (lots of measurements taken from individual collars in the field). On page 46 of their report they note:

> "Most of the studies in this review use a similar experimental design. The majority are paired-site comparisons with repeated measures at the same points in the same installed chambers in each site over time. Only a few studies have taken baseline data. A repeated measure on the same fixed collar, used to place gas measurement chambers, inserted into the surface of the soil reduces the external validity, i.e. reduces the generalisation of results to other situations, of most studies, particularly as sample size is often low. While the use of fixed sample points reduces variability in the data due to spatial variation, allowing a clearer picture of temporal change, sufficient replication needs to be employed for that temporal pattern to be indicative of the whole site and not just the small areas covered by each collar.
>
> "There is also often only one drained or re-wet site and one control site with several collars inserted in each. Allocation of treatment is often not random, with measurement being carried out after implementation of land management practices. While the sites may not necessarily be available, greater replication at the field/site level would also improve the external validity of most studies. However, for those intervention-outcome combinations where there are a large number of effect sizes over a wide geographic range, the meta-analysis may partly compensate for the lack of external validity."

Although right to question the quality of previous studies on statistical grounds, **Bussell *et al*. (2010)** show some lack of understanding of some practical aspects of field research. Collars could be placed in many locations and visited just once during a measurement period (a season or year) to avoid repeated measures. However, the problem here is one of trampling damage to field sites and the time and cost (of labour) of constantly re-positioning collars. The ground around fixed collars that are visited regularly can be protected with boardwalk, while routes that minimise trampling damage can be set up between such collars. Nevertheless, there is merit in trying to increase the spatial sample size of flux chamber studies and this can be done on a campaign basis where many collars are sampled over a short time period to gain a picture of short-term spatial variability in fluxes. It should be also noted that our field experimental design includes replication (we will have four cases of each treatment).

Notwithstanding these criticisms of **Bussell *et al*. (2010)**, their contention that previous work can and must be improved upon in properly-replicated and carefully-designed trials is a good one and one that the current study (SP1202) will address as far as is practicable.

Although it has its own limitations, the study of **Bussell *et al*. (2010)** provides a useful summary of what is known about the effect of drainage and re-wetting on peatland-atmosphere GHG exchanges. **Bussell *et al*. (2010)** conclude (p. 47) that there is strong evidence that drainage decreases CH_4 emissions and increases losses of N_2O and net losses of CO_2, such that, when these gases are considered together, the effect is one of an increase in peatland global warming potential (GWP). They note that the evidence that re-wetting of peat causes an increase in CH_4 emissions and a decrease in N_2O emissions is weaker. They found no clear evidence of an effect of re-wetting on CO_2 exchanges. However, as noted by **Bussell *et al*. (2010)**, the latter conclusions are affected by the small number of suitable studies for inclusion in the meta-analysis.

3.2 The role of Sphagnum *in CH_4 losses from restored peatlands*

As noted in the final report of Defra project SP0574 (**Baird *et al*., 2009**) there is empirical evidence to suggest that CH_4 emissions from sites dominated by *Sphagnum* are less than those from sites dominated by sedges (cotton grasses). **Lindsay (2010)** stresses the importance of *Sphagnum* in reducing CH_4 emissions but perhaps over-emphasises the current state of knowledge by relying too much on the results from one study.

Lindsay (2010) notes that *Sphagnum* reduces the vigour of sedges (such as cotton grasses) and acts to oxidise any CH_4 escaping upwards through the peat. In support of the latter he cites **Frenzel and Karolfeld (2000)** who, to use **Lindsay's (2010)** words:

> "...found that CH_4 production in ... hollows was very much higher than the observed emissions of CH_4, leading them to conclude that 99% of CH_4 production was oxidised before emission ... In A1 *Sphagnum* hollows, they found no trace of CH_4 down to the base of the green parts of the *Sphagnum cuspidatum* carpet at a depth of 7 cm, but below this the CH_4 level steadily increased. Frenzel and Karofeld (2000) therefore concluded that CH_4 oxidation was being driven by photosynthetically-derived oxygen, rather than by penetration of air into the *Sphagnum* carpet."

Lindsay's (2010) reading of **Frenzel and Karofeld (2000)** and his assumption that *Sphagnum* carpets will eventually overwhelm sedges in restored peatlands would seem to suggest that CH_4 emissions from restored peatlands will not be a long-term problem. There are two difficulties with this view. First, a post-restoration spread of *Sphagnum* will not necessarily occur as noted in the discussion in section 3.1. Secondly, the measurements taken by **Frenzel and Karofeld (2000)** do not make as strong a case for the 'oxidising power' of *Sphagnum* as suggested by **Lindsay (2010)**.

Frenzel and Karofeld (2000) used flux chambers similar to that in the Figure 3.1 of **Baird *et al*. (2009)** to measure CH_4 fluxes from a range of different habitat types on a raised bog in Estonia. Their flux chamber data suggest that CH_4 emissions to the atmosphere from *Sphagnum cuspidatum* hollows are very low indeed (< 5 mg CH_4 m^{-2} d^{-1} – converted from Frenzel and Karolfeld's units of μmol m^{-1} h^{-1}) and much lower than from areas dominated by sedges such as *Eriophorum vaginatum* L. (Hare's Tail Cotton Grass) (> 360 mgCH_4 m^{-2} d^{-1}). **Frenzel and Karolfeld's (2000)** measurements of pore-water CH_4 concentrations, to which Lindsay refers, are reproduced below as Figure 2.1 (Figure 8 from **Frenzel and Karofeld (2000)**). These do indeed show pore-water CH_4 concentrations dropping to what appear to be close to atmospheric ambient values as (moving upwards) the base of the depth of maximum photo-penetration in the *Sphagnum* is reached.

In themselves, both sets of data seem to provide a very strong case for the re-establishment of *Sphagnum* as a means of controlling CH_4 emissions from restored peatlands. However, the data from **Frenzel and Karofeld (2000)** are not as clear as they could be. Although the authors provide standard error (SE) bars for their flux chamber data, they do not indicate how many measurements were taken. This is important because they may have taken rather few measurements and missed ebullition events. In such circumstances the data may be misleading; that is, it is possible –even likely – that what they measured were diffusive fluxes and fluxes through plant tissue and not ebullition. Therefore, they could have missed an important component of the CH_4 emissions picture. As noted in **Baird *et al*. (2009)**, use of the normal chamber method (NCM) may lead to significant underestimates of CH_4 fluxes from some peatlands.

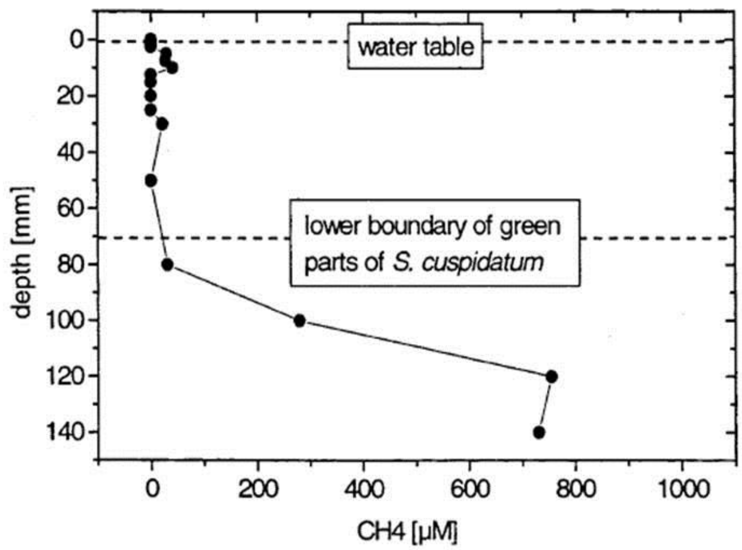

Figure 2.1. *Dissolved CH_4 concentrations in a core of peat containing a growing layer of* Sphagnum cuspidatum*. Reproduced from Frenzel and Karofeld (2000).*

It is interesting that **Frenzel and Karofeld (2000)** separately measured CH_4 fluxes via ebullition using inverted funnels on the edge of pools. In a funnel or funnels (it is not clear which from the paper) deployed for 25 hours at pool edges in which *Sphagnum cuspidatum* was found, rates of CH_4 emission were 21 mg CH_4 m^{-2} d^{-1}, more than four times higher than flux chamber estimates from *Sphagnum cuspidatum* hollows. Although still rather low, such rates of loss show that the presence of *Sphagnum* does not necessarily shut down CH_4 emissions to negligible values. It is also possible that with a longer deployment, the funnel(s) would have shown higher time-averaged fluxes because the chances of them recording an episodic ebullition event would have been increased (see section 3 of **Baird *et al*. (2009)**).

The pore water data shown in Figure 2.1 look compelling but they also show that CH_4 concentrations at depths of 120 mm (12 cm) are (probably) above the equilibrium concentration (which depends on the presence of other gases) such that methane-containing bubbles may be present and may be lost directly to the atmosphere (*cf*. **Baird *et al*., 2004**; **Kellner *et al*., 2006**). Therefore, the pattern of (upwards) decline in pore-water CH_4 concentrations shown in Figure 2.1 cannot be used to indicate that all CH_4 that is produced is oxidised. In any case, numerous studies – including flux chamber studies –show relatively high CH_4 emissions from *Sphagnum* lawns and hollows (see **Baird *et al*., 2009**). It is misleading to place so much emphasis on a single paper, and part of a single paper at that.

It is worth emphasising that *Sphagnum* is not always an important component (in terms of abundance) of blanket peatland vegetation, and that restoration will not necessarily lead to an increase in *Sphagnum* cover. For example, **Sottocornola and Kiely (2005)** report on flux tower measurements of net ecosystem exchange (NEE) at Glencar, an apparently undamaged patterned Atlantic blanket bog in County Kerry, Ireland. The site was discussed in **Baird *et al*. (2009)** when presenting the results from the studies of **Laine *et al*. (2006)** and **Laine *et al*. (2007)** (see section 5.1 of **Baird *et al*. (2009)**). **Sottocornola and Kiely (2005)** note that only 10 percent of the total plant cover of the site comprises bryophytes and that this percentage is shared between the Sphagna and non-*Sphagnum* species such as *Racomitrium lanuginosum* Brid..

3.3 The role of sedges in CH_4 emissions from peatlands

The reviewed reports, except **Couwenberg (2009)** (see below), add little to what was said in **Baird *et al*. (2009)** about the role of sedges in CH_4 production, oxidation and transport in peats. Two papers not discussed in **Baird *et al*. (2009)** were looked at. The first – **Marinier *et al*. (2004)** – considers carbon gas exchanges in tussocks of the sedge *Eriophorum vaginatum* (Hare's Tail Cotton Grass) as measured using flux chambers. Despite some methodological problems with the analysis of their flux chamber data (they appear to have excluded data sets with outliers that might have indicated ebullition), **Marinier *et al*. (2004)** found that CH_4 emissions from *E. vaginatum* tussocks show a significant positive (or direct) linear relationship with above-ground biomass and with photosynthetic rate. When fresh leaves were clipped from tussocks, CH_4 emission rates dropped by 79 percent. Interestingly, **Marinier *et al*. (2004)** found that some tussocks showed a net loss of CO_2 to the atmosphere, and concluded that *E. vaginatum* tussocks provide little or no net carbon accumulation. However, their study should be put in context. Their research sites were cut-over peat surfaces that had been fertilized as part of the restoration treatment, and their CO_2 exchange data, in particular, may reflect this intervention. Their results are helpful, though, in showing that, in areas where sedges dominate, a large proportion of CH_4 may be derived from recently-fixed carbon.

Currently-unpublished results from a recently-completed NERC project managed by Andy Baird (NE/F003390: *Efflux of methane (CH_4) to the atmosphere from northern peatlands via ebullition: the role of plants and peat structure*) show that paired peat samples from raised bog hollows show very different carbon gas dynamics according to their cover of another sedge – *Eriophorum angustifolium* Honck. (Common Cotton Grass). Under laboratory conditions where water tables and meteorological conditions (light, temperature, humidity, and rainfall) were held the same for all samples, summertime fluxes from those containing *E. angustifolium* + *Sphagnum cuspidatum* were more than 100 mg CH_4 m^{-2} d^{-1} higher than those containing *Sphagnum cuspidatum* alone. Nevertheless, fluxes from the latter were not negligible and regularly exceeded 30 mg CH_4 m^{-2} d^{-1}.

The recent study of **Wilson *et al*. (2009)** appears to be a follow on to the study of **Wilson *et al*. (2007)** (cit. **Höper *et al*. (2008)**) (see section 5.2 of **Baird *et al*. (2009)**). It considers differences in CH_4 emissions from different plant communities developed on fen peat exposed by removal ('harvesting') of the upper layers of peat from a raised bog. These communities, which include ones dominated by *Phalaris arundinacea* L. (Reed Canary Grass) and *Typha latifolia* L. (Reedmace) would not normally be found in blanket peatland and the study seems to have little relevance to the current project (SP1202). In addition the study suffers from the problem of poor replication identified by **Bussell *et al*. (2010):** only two to four collars of 60 × 60 cm were used in each plant community type. Therefore, its results are not considered here.

In a meta analysis of studies on CH_4 emissions from peatlands, **Couwenberg (2009)** suggests that water level and so-called 'shunt'[2] species of plants (sedges and grasses) are good predictors or indicators of annual CH_4 emissions. His analysis comprises studies from fens and raised bogs, but not, apparently, blanket bogs. The study provides a good first step in producing emissions factors for re-wetted peatlands, and for this purpose Couwenberg makes a binary distinction between wet and dry sites and sites with and without 'shunt' species. He defines wet sites as those with annual average water tables at depths less than 20 cm, and dry sites as those with depths greater than 20 cm. He does not present any model fits to his data sets, and there appears to be considerable scatter in the relationship between CH_4 emissions and water level in particular. To illustrate the

[2] Couwenberg uses 'shunt' to describe any plant species in which CH_4 may be transported from the rhizosphere to the atmosphere. He uses the term to describe situations where such transport through the plant tissue is diffusive and where it is pressure-driven (advective). Strictly, the term should be reserved for the latter.

relationship between annual CH_4 emissions and annual average water level **Couwenberg (2009)** reproduces results from **Drösler (2008)** (cit. **Couwenberg (2009)**) for a single study site. Although the relationship is strong it shows considerable scatter, with a modest r^2 of 0.54. In conclusion, **Couwenberg's (2009)** analysis is promising for setting emissions factors, but its usefulness for understanding how peatland management, re-wetting in particular, affect CH_4 emissions is less clear. It suggests that CH_4 emissions are higher when water levels are higher and when certain species of sedges and grasses are present, but that is already known. What is not answered in **Couwenberg (2009)** is the longevity of any increases in post-wetting CH_4 emissions on a restored site.

3.4 The role of grazing in the peatland carbon cycle

The role of grazing in peatland carbon-balance processes was not reviewed in **Baird *et al*. (2009)**. However, it is clearly useful to know how grazing affects the species composition and cover of vegetation on restored sites and how, in turn, these affect other components of the carbon cycle. The review by **Schils *et al*. (2007)** is particularly helpful here. They note (pp. 82-83) (square brackets indicate our additions):

> "Although peatlands are in general less intensively grazed, they may be highly sensitive to grazing impacts (Haigh, 2006). C accumulation in peatlands is dependent on the presence of plant species that generate decay-resistant litter, such as *sphagnum* [*sic*] mosses (Belyea, 1996), which may be affected by grazing intensity. Ward *et al.* (2007) found moderate reductions in dwarf shrub and moss biomass with grazing, versus long-term ungrazed controls. Smith *et al.* (2003) found that complete cessation of grazing on ombotrophic [*sic*]mires resulted in growth of dwarf shrubs and hypnoid mosses at the expense of peat-forming *sphagnum*. This result suggests that grazing, at a low intensity, may be beneficial to maintaining the C sink, at least in areas of dryer/drained peatlands. However, where effects on C cycling have been measured, results are unclear. Garnett *et al.* (2000) found no significant difference in long-term C accumulation on grazed and ungrazed peatland in the 50 year Hard Hills exclusion experiment [an area of Moor House in the North Pennines] in Northern England. For the same experiment, Ward *et al.* (2007) measured a 22% reduction in above-ground biomass with grazing, a stimulation of both photosynthesis and respiration, a large increase in CH_4 efflux and small increase in DOC [dissolved organic carbon] loss, non-significantly lower carbon stocks in the litter layer and upper mineral soil layers, but no measurable difference in soil C stocks to a depth of 1m. Worrall *et al.* (2007) found no effect of grazing on DOC at the same site.
>
> "Effects of trampling associated with grazing are more severe on peats, due to the low bulk density and depth of the organic layer; Overgrazing [*sic*] has been a major cause of blanket peat erosion in Northern England (Haigh, 2006; Holden *et al.*, 2007), with erosion triggered by relatively low stocking densities (0.55 sheep ha^{-1}, Rawes and Hobbs, 1979). Erosive effects may be concentrated in areas of livestock movement or shelter, with compaction causing an increase in overland flow and potentially triggering or accelerating gully development."

We checked **Ward *et al*. (2007)** and are obviously familiar with the content of **Holden *et al*. (2007)** and the summary of **Schils *et al*. (2007)** is accurate in how it describes these papers. Therefore, it is probably accurate about the other papers that are reviewed. Grazing effects are likely to be strongly influenced by grazing density and the climate of a blanket peatland site, and it would be unwise to apply uncritically results from one blanket peatland to another site where stocking regime and/or climate are different. It is also evident that results from the same site (the Hard Hills experiment noted above) are to, some extent, conflicting. What is probably not in doubt is that grazing beyond a certain intensity can lead to a reduction in cover of shrubs/ericoids, but whether this reduction affects sedge and moss cover and the components of the carbon budget is unclear. Finally, grazing can be a cause of peat erosion, although threshold densities where erosion is triggered probably vary between sites.

3.5 *The effect of grip blocking on particulate and dissolved carbon production in and losses from peatlands*

There is little to update here from the review of **Baird *et al*. (2009)**. **Höll *et al*. (2009)** compared the dissolved organic matter (DOM) concentrations between adjacent drained and re-wetted peatland sites. However, the sites were fen peats (see **Fiedler *et al*. (2008)**) supplied with water from karstic springs, and their study had some potentially serious methodological shortcomings. For example, they looked at dissolved organic carbon (DOC) concentrations at five depths, but did so at only three locations in each study site which would be insufficient to 'capture' any spatial variability within each site. Nevertheless, they found statistically significant differences between the sites, with the re-wetted site having lower DOM concentrations than the drained site. A problem in the current context is the extent to which the results from **Höll *et al*. (2009)** are transferable to blanket peatlands. The vegetation and hydrochemical properties of the fen peats investigated by **Höll *et al*. (2009)** are very different from those in blanket peats and it is not clear how conditions in blanket peat pre- and post- grip blocking act to change the processes responsible for DOC production.

The meta-analysis of **Bussell *et al*. (2010)** found clear evidence that drainage causes a significant increase in DOC concentrations. However, **Bussell *et al*. (2010)** found no clear evidence of an effect of re-wetting on DOC concentrations, although their analysis was based on data from just three studies (**Meissner *et al*. (2003)** (fen) cit. **Bussell *et al*. (2010)**; **Moore and Clarkson (2007)** (bog) cit. **Bussell *et al*. (2010)**; **Wallage (2007)**[3] (bog)). They acknowledge the dearth of reliable studies from which to draw wider conclusions and strongly recommend that future studies establish baseline conditions and are well-replicated.

The most recent study on the effects of grip blocking on DOC dynamics (in the water in the grips) is that of **Armstrong *et al*. (2010)**. This study, referred to in **Baird *et al*. (2009)** as **Armstrong *et al*. (2009 in review)**, was not available to **Bussell *et al*. (2010)** but found that, in general, drain blocking in blanket peatland reduces DOC concentrations within the channels, although at some sites there was no difference between drained and re-wetted. **Armstrong *et al*. (2010)** 'spot sampled' 320 grips from 32 sites (266 blocked grips, 49 unblocked, and 15 where the status was indeterminable). They used backwards stepwise regressions to investigate controls on DOC concentrations and found that easting, rainfall, drain depth, whether a drain was blocked, days blocked, drain cross-sectional area, whether it was grazed and whether heather (*Calluna vulgaris* (L.) Hull.) was present were all significant. Of these explanatory variables, (higher) rainfall, (greater) drain depth and blocked drains were associated with lower DOC concentrations. The remaining variables were positively related to DOC concentrations.

When considering the effect of drainage on DOC production, **Lindsay (2010)** (p. 145) noted:

> "It is worth noting that any increase in vascular-plant biomass is likely to occur at the expense of the biomass of *Sphagnum*. Consequently the overall biomass of the vegetation cover may remain the same or even decline, but the important thing in terms of DOC production is that the proportion of vascular-plant tissue within the biomass has increased. Meanwhile, more active and extensive root systems can greatly enhance decomposition processes within the acrotelm. If the water table is drawn down into the catotelm along a drain margin, vigorous root growth of species such as heather (*Calluna vulgaris*) can stimulate the decomposition of recalcitrant catotelm peat in the manner suggested by Fontaine *et al.* (2007)."

The study referred to here by Lindsay – **Fontaine *et al*. (2007)** – considered the role of labile (easily decomposed) organic compounds in the decomposition of old, non-labile, soil organic matter (SOM). **Fontaine *et al*. (2007)** found that decomposition of old, non-labile SOM could be stimulated by the addition of cellulose, an important component of plant litter. The cellulose provides a ready energy supply to decomposers allowing them to break down older, more recalcitrant SOM. Lindsay seems to be suggesting that exudates from *Calluna*

[3] This study was reviewed in **Baird *et al*. (2009)** but via its published output in **Wallage *et al*. (2006)**.

roots, or the roots themselves, are the source of labile carbon compounds that stimulate decomposers so that that they can degrade catotelm peat. *Calluna* roots certainly contain large quantities of cellulose (**Martinez *et al*., 2002**). What Lindsay suggests seems plausible in the zone above the water table close to drainage ditches. However, it is worth emphasising that **Fontaine *et al*. (2007)** also note that their results "cannot apply to waterlogged peat soils, because decomposition there is primarily constrained by a lack of oxygen.". In other words, we should not dismiss the important role of anoxia in preventing the decay of peat. While *Calluna* roots may stimulate decay in the drawdown zone adjacent to ditches, decomposition and the production of DOC may also be stimulated by oxygen penetrating more deeply into the peat after drainage.

3.6 Other carbon balance studies on restored peatlands

Two papers missed from **Baird *et al*. (2009)** are **Glatzel *et al*. (2004)** and **Yli-Petäys *et al*. (2007)**. The former considers the CO_2 and CH_4 production potential of peat samples taken from a range of natural, cutover, and restored bogs. Production potential was measured in the lab.; for CO_2 in both aerobic and anaerobic conditions, and for CH_4 in anaerobic microcosms only. For both aerobic and anaerobic conditions, CO_2 production potential was higher for surface peat samples than for samples taken close to the water table. A similar pattern was observed for CH_4 production potential, with the highest rates measured for surface samples from a natural bog site and from an inundated former block-cut site that had become colonised by floating mats of *Sphagnum fallax* (Klinggr.) Klinggr. and the ericoid shrub *Chamaedaphne calyculata* (L.) Moench. The findings of **Glatzel *et al*. (2004)** suggest that newly-formed peat, including in restored sites, is readily decomposable, and, if below the water table, may be highly productive of CH_4. Their results do not consider litter production, but the authors suggest that the high rates of decomposition may mean that net C uptake in restored peatlands is relatively low; however, they do not say why this is or how C dynamics in restored sites compare with natural sites.

Yli-Petäys *et al*. (2007) studied CO_2 and CH_4 exchanges in areas on a formerly cut-over peatland that had self-restored over 50 years previously. They looked at areas with four plant communities or assemblages that resembled those in natural sites and measured CO_2 and CH_4 exchanges using flux chambers. Using a combination of measurements, models based on the measurements, and assumed fluxes they found that three of the communities had a net C loss in each of the two years considered (2000 and 2001). In the fourth community there was a net loss of C in 2000 and a net uptake in 2001. However, when the net C uptake for 2001 is expressed in global warming potential (GWP) terms, the fourth community was strongly radiatively warming: GWP based on the average CO_2 and CH_4 fluxes for that community was >1000 g CO_2-e yr^{-1} over a 100 year time frame (see **Baird *et al*. (2009)**). **Yli-Petäys *et al*. (2007)** rightly caution that their study covered two years only and that large inter-annual variability in CO_2 and CH_4 fluxes can occur. But what their results do show is that the conclusions from an earlier study by **Tuitilla *et al*. (1999)** (reviewed in **Baird *et al*. (2009)**), which suggested that restored peatlands could be strong C sinks and that CH_4 emissions did not substantially affect GWP, could be premature; well-established restored peatlands may be modest C sinks and quite strongly radiatively forcing because of sustained CH_4 emissions.

4. Summary

This brief report supplements **Baird *et al*. (2009)** (Defra SP0574). Review of the latest information on grip blocking techniques used in the UK has shown that re-profiling or partial infilling of ditches, in particular with peat scraped from the peatland surface adjacent to the ditch, may prove increasingly popular. It has also become clear that heather bales are used for ditch infilling as well as for dams or 'filters'.

This update confirms that sedges are associated with higher CH_4 emissions from peatlands than areas dominated by *Sphagnum* mosses. However, we caution against over-interpreting the work of **Frenzel and**

Karofeld (2000), which suggests that *Sphagnum*, through its hosting of methanotrophs, may remove almost all of the CH_4 that is produced in the peat profile. Other work shows that CH_4 emissions can still be quite high from *Sphagnum*-dominated areas (>30 mg CH_4 m^{-2} d^{-1}) and that it is not clear whether *Sphagnum* will always increase in cover with time after restoration. The evidence-base regarding increases in CH_4 emissions post-restoration of peatlands is still limited (five studies found by **Bussell *et al*. (2010)**). It is sometimes assumed that the post-restoration increase in CH_4 emissions will be short-lived, especially in bogs, as *Sphagnum* recolonises a site (**Lindsay, 2010**). However, the only study we could find of an old, well-established restored site (**Yli-Petäys *et al*., 2007**) suggests CH_4 emissions can remain high and that a restored peatland with close to natural plant assemblages may not be a strong C sink.

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6. Systematic review

In addition to the literature review above, we undertook a systematic review of the literature for work done on UK blanket peatlands so that we could put the site used for the field trials (see main report, sections 1.3 and 2.1) in context. The systematic review was conducted in July 2014. Both the formally-published and grey literature were considered. The following search sites were used:

- Web of Knowledge (http://wok.mimas.ac.uk/)
- Google Scholar (http://scholar.google.co.uk/)
- Science Direct (http://www.sciencedirect.com/)
- BioOne (http://www.bioone.org/).

In addition, a general internet search (using Google) was undertaken to ascertain the extent of the grey literature.

The following search terms were used:

- **"blanket peatland*" AND "UK"**
- **"blanket peatland*" AND "restored"**
- **"blanket peatland*" AND "UK" AND "restored"**
- **"blanket peatland*" AND "UK" AND "restored" AND "peat properties"**
- **"blanket peatland*" AND "UK" AND "restored" AND "physical properties"**
- **"blanket peatland*" AND "UK" AND "restored" AND "water table"**
- **"blanket peatland*" AND "UK" AND "restored" AND "bulk density"**
- **"blanket peatland*" AND "UK" AND "restored" AND "loss on ignition"**
- **"blanket peatland*" AND "UK" AND "restored" AND "electrical conductivity"**
- **"blanket peatland*" AND "UK" AND "restored" AND "peat pH"**
- **"blanket peatland*" AND "UK" AND "soil solution pH"**
- **"blanket peatland*" AND "UK" AND "soil solution electrical conductivity"**
- **"blanket peatland*" AND "UK" AND "gravimetric water content"**
- **"blanket peatland*" AND "UK" AND "volumetric water content"**
- **"blanket peatland*" AND "UK" AND "soil C:N"**

The results of the review are contained in an Excel workbook (Appendix B). Not all articles/books/reports identified by the search contained the information we were seeking. These 'null' returns are listed at the end of the Excel data base.