Peatland Biodiversity

David JT Douglas[1], Peter S Jones[2], Ian Crosher[3,4], Iain Diack[5], Nick Littlewood[6]

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Monitoring biodiversity responses to peatland restoration

David JT Douglas[1], Peter S Jones[2], Ian Crosher[3,4], Iain Diack[5], Nick Littlewood[6]

[1]RSPB Centre for Conservation Science, RSPB Scotland, 2 Lochside View, Edinburgh Park, Edinburgh, EH12 9DH
[2]Natural Resources Wales
[3]Natural England, (Head Office) Foss House, Kings Pool, 1-2 Peasholme Green, York, YO1 7PX
[4]Ghyll Mount, Penrith Business Park, Penrith, Cumbria, CA11 9BP
[5]Natural England, Parkside Court, Hall Park Way, Telford, TF3 4LR
[6]Conservation Science Group, Department of Zoology, The David Attenborough Building, University of Cambridge, Cambridge, CB2 3QZ

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Add in some graphs of bird responses (eg GP dunlin), craneflies etc – that would be useful for giving presentations and illustrating the speed of recovery.

Summary

This technical report informs the 2018 update of the 2011 IUCN UK Peatland Programme Commission of Inquiry on peatlands (Bain et al 2011). Here we assess the extent of biodiversity monitoring at peatland restoration projects in the UK, review the existing evidence base of biodiversity responses to peatland restoration, provide a critical review of whether current UK monitoring is sufficient to enable responses to be robustly measured and provide guidance for future biodiversity monitoring of peatland restoration.

Responses to a questionnaire survey sent to 55+ contacts who were either attached to known restoration projects, or otherwise involved in UK peatland restoration, enabled us to summarise biodiversity monitoring at 12 UK restoration projects, 11 of which undertake monitoring. This is known to be only a small sample (max. 6%) of the c200+ UK peatland restoration projects. It is unknown whether the respondents comprise the majority of projects undertaking biodiversity monitoring. Vegetation was reported to be monitored in some form at all 11 sites, invertebrates and birds at 9 sites, reptiles, amphibians and mammals at 4 sites and microbes at 2. The extent of monitoring of key taxa that may provide measurable targets for assessing restoration, such as Sphagnum mosses and craneflies, was unclear across sites. The popularity of monitoring some other taxa may relate to project or organisational priorities rather than selection based on their being the optimum taxa to use for assessing peatland recovery. Use of formal study designs was limited. Only four instances of Before-After-Control-Impact (BACI) designs were reported, all relating to vegetation. Other study designs that should enable robust testing of biodiversity responses were also limited, with four instances of Control-Impact (CI) designs; vegetation (1), invertebrates (1), birds (1) and mammals (1) and six instances of Before-After (BA) designs; vegetation (2), invertebrates (1), reptiles (1) and birds (2). Monitoring timescales and the extent of taxon-specific monitoring also differed between sites, which may limit the inferences that can be made in terms of restoration trajectories across sites. The variation in monitoring between sites may relate to the absence of any overarching co-ordination of peatland monitoring in the UK. Reported spend on biodiversity monitoring varied widely across sites and the median was 1.1% (range 0.3 to 37.7%) of total project budget. If two nature reserves with the highest spend are excluded, the mean spend across the remaining three sites providing figures was just 0.7% of overall budget. Based on questionnaire responses, most monitoring resources are spent on in-house staff costs rather than outsourced monitoring.

Across temperate peatlands globally, translation of biodiversity monitoring into peer-reviewed papers and grey literature varies between taxa. Some taxa are clearly under-represented globally; for example, in a sample of 179 papers or reports identified as suitable for review, birds feature in just 3.4% (n=6) of these, amphibians 0.6% (n=1), mammals 1.1% (n=2) and we found no published studies addressing responses of reptiles to peatland restoration. Vegetation was better represented, with 80.4% (n=144) of papers addressing vegetation responses to restoration, and invertebrates were also reasonably well represented (18.4% of papers, n=33). The reported evidence does suggest that, for some taxa such as birds, responses to restoration can be rapid and in expected directions. A lack of robust evidence of biodiversity responses to restoration, particularly over the required timescales (multiple decades), could have implications for the ability of governments to

accurately assess their contribution to achieving targets for biodiversity restoration, notably the Aichi biodiversity targets of the Convention on Biological Diversity (CBD). It is worth noting that some biodiversity indicators such as vegetation could also act as potential proxies of likely carbon/greenhouse gas responses to restoration, adding to the value of monitoring biodiversity at restoration sites. A weak evidence base across different taxa also means that the most effective restoration techniques may not be adequately known and information on them is not being used to guide future restoration. Large sums of government funding are being used for peatland restoration and it is important that this is deployed effectively to achieve value for money. We strongly encourage the formal analysis and publication of further biodiversity monitoring. This could be achieved for example through making a percentage of restoration money available for analysis and publication of monitoring data.

In terms of UK monitoring, we recommend a more robust approach to biodiversity monitoring of peatland restoration. A key recommendation is that a network of exemplar sites, deploying consistent approaches, should be developed and supported by appropriate funding. Formal study designs that enable robust testing of responses (in particular BACI but also CI or BA) should be utilised. Monitoring that lacks both a baseline and controls is unlikely to yield useful data and will not be cost-effective. Taxa monitored should enable measurable biodiversity restoration targets to be assessed. As a minimum, this should include *Sphagnum* mosses, ideally to species level, plus additional keystone taxa such as craneflies, which can be indicators themselves of peatland condition such as moisture levels, and are also important in peatland food webs. Consistent methods should be used for individual taxa, both within a site over time and across different sites. Monitoring should continue over a sufficient (long-term) timescale to assess responses (for example 2, 5, 10, 20 and 30+ years post-restoration). Progress towards recovery outcomes should be assessed periodically, using on-site monitoring data. This will enable remedial works to be deployed if restoration is not progressing as expected, using an adaptive management approach. Sufficient funding (for example 5% of overall restoration costs) should be made available for biodiversity monitoring. There is scope for more co-ordinated use of citizen science and volunteers and potential for greater use of remote sensing vegetation change. Data should be shared to enable collaborative meta-analyses of biodiversity responses to be undertaken. Finally, biodiversity monitoring at UK peatland restoration sites should be co-ordinated by a single body to ensure consistency in approach, and that body should also receive and store monitoring data.

1. Introduction

1.1 Why monitor biodiversity responses to peatland restoration?

Peatland restoration is identified as a priority action under international agreements for achieving biodiversity conservation and carbon targets (CBD, 2018). Whilst restoring carbon storage and sequestration processes and hydrological aspects (water quality, flow rates and flood risk management) may be commonly viewed as the environmental drivers for peatland restoration, a previous review of UK peatland restoration projects found that biodiversity conservation was stated as the primary reason for restoration (Defra 2008). Indeed, carbon and water are services derived from healthy, active peatlands of which the characteristic biodiversity are of fundamental functional as well as conservation importance (Littlewood et al 2011). This functional importance includes the role of key peat-forming plants such as *Sphagnum* mosses, microbes that play a role in gas flux, as well as higher taxa that may be keystone species in peatland food webs (e.g. craneflies (Tipulidae)) or of conservation importance (amphibian, reptile and bird communities) (Littlewood et al 2011). Many of the characteristic plants and animals of healthy/active peatland ecosystems also tend to be restricted to the conditions found in these environments. Thus, although in situ species diversity at peatlands ('alpha diversity') can be low for a particular biological group (Littlewood et al 2011), the specialised peatland species add significantly to regional ('beta') diversity.

Understanding the way that biodiversity responds to peatland restoration is therefore fundamental for understanding how well a peatland is likely to be functioning post-restoration. Understanding biodiversity responses to peatland restoration could also have wider implications relating to funding for restoration. A significant current barrier to peatland restoration is financial; although some public funding is available for peatland restoration in parts of the UK (Defra 2018; SNH 2018a; BBC 2017) it may not be sufficient in relation to the areas that need to be restored, and is also competitive. Hence, it is important to know not just how best to restore peatlands, but how to maximise the efficacy of this and restore the largest areas, well enough. Reform of agriculture subsidies is being proposed by Defra towards a system that would provide payments for public benefits. Understanding and quantifying biodiversity benefits arising from land management will be important for such initiatives.

Even with reform of public payments, additional private funding sources are required and one such source is the voluntary carbon market. To access the voluntary carbon market, buyers need to be given assurance that the climate benefits are real, quantifiable, additional and permanent. The Peatland Code is the mechanism through which such assurances can be given (IUCN UK Peatland Programme 2018) and is a voluntary standard for UK peatland projects wishing to market the climate benefit of restoration. It sets out a series of best practice requirements including a standard method of quantification which, when validated by an independent body, which could be the same body that coordinates peatland monitoring, will give assurance to buyers that their purchase will return verifiable climate benefit over the project duration. The Peatland Code could potentially include biodiversity as a 'biodiversity credit' metric (Smyth et al 2015), but this would require reliable data from

UK peatlands to help build the case for investment based on demonstrable evidence of responses.

Therefore, for both assessing functional and conservation responses of biodiversity to peatland restoration, and facilitating potential funding, there is a need to test, quantify and demonstrate benefits of restoration. This relies on robust monitoring of biodiversity responses to peatland restoration. Despite this, monitoring and testing responses to restoration has so far focused largely on hydrology (including responses in water tables, flow rates and water quality) or carbon status (e.g. Wilson et al 2011). Monitoring of biodiversity responses to UK peatland restoration has been viewed as patchy (Defra 2008), consistent with previous IUCN-commissioned reviews that have highlighted the absence of long-term targeted biodiversity monitoring data as a major factor limiting our understanding of the effectiveness of peatland restoration (Lunt et al, 2011, Littlewood et al, 2011, Parry et al 2014, Andersen et al 2017). This has prompted calls for a more co-ordinated approach to monitoring. Furthermore, whilst some studies of biodiversity responses to restoration have been translated into peer-reviewed papers, the overall extent of the evidence base, the representation of different taxa within it, and what it tells us about biodiversity responses to restoration, was unclear at the outset of this review.

There is therefore a need to assess and critique the current extent of biodiversity monitoring at peatland restoration sites in the UK, review the evidence-base of studies and make recommendations, if required, for future monitoring in the UK. It is not our intention here to review the importance of peatland biodiversity per se, as this has been previously covered, in particular with reference to blanket bog (e.g. Littlewood et al, 2011). Rather, here we focus on monitoring of biodiversity (the range of living taxa) responses to restoration within the main peatland types that occur in the UK (blanket bog, lowland raised bog and lowland fens and mires).

This work is timely as some of the UK's devolved administrations have recently developed (Natural England 2016; SNH 2018a), or are currently developing strategies for peatland restoration (eg Defra's 25 Year Environment Plan includes a statement to publish an England Peat Strategy in late 2018, Defra 2018)..

1.2 What should be the biodiversity goals when restoring peatlands?

Various authors have considered goals for peatland restoration, but a useful summary of restoration aims can be taken from Gorham and Rochefort (2003):

> *"Successful restoration must meet the goal stated by the U.S. National Research Council (NRC, 1992): 'to emulate a natural, functioning, self-regulating system that is integrated with the ecological landscape in which it occurs'. It will encompass returning the ecosystem to the structure, function, trophic organization, and biodiversity characteristic of its type (Rochefort, 2000). It would be helpful if a set of 'indicator species' could be identified as useful in showing the re-establishment of various ecosystem functions (Zedler and Weller, 1989; Bakker et al., 2000)". Reflecting the timescales involved in restoring peatland function,*

monitoring will be required over several decades (Bakker et al., 2000). Over the longer term it is important to re-establish, as far as possible,
(1) full biodiversity, taking into account its different levels (genetically different ecotypes, species, ecosystems and landscapes),
(2) trophic organization of plants and animals into food webs resembling those present before disturbance, and
(3) productivity, decomposition, and biogeochemical cycles characteristic of the original type of ecosystem and balanced, so that peat accumulates.
In evaluating long-term success it will be necessary to take into account all of the ecosystem properties listed above, and to pay attention to environmental factors that may influence recovery: hydrology, alkalinity/acidity, and nutrients (Bridgham et al., 1996; see also Wheeler, 2000)."

In the similar field of riverine ecology, Natural England's 'Narrative on conserving freshwater and wetland habitats in England' (Natural England 2016) deals with the principles of restoration in modified landscapes, and provides guidance on establishing likely 'reference' environmental states and possible end-points, based largely on re-instatement of natural environmental processes. In such a case, where millennia of human intervention have modified habitats, restoration end-points can be difficult to base on original status and choices must involve other criteria, particularly as climate may further modify habitats. These choices will require societal and ecological decisions based, for example, on the desirability and ease of re-establishing rare species or the types of ecosystems possible to restore (Beltman et al 1995), or providing habitat for certain kinds of wildlife such as birds (Bölscher 1995; Desrochers et al 1998) or butterflies (Duffey and Mason 1970). At present, "societal decisions" often promote peatland restoration in quite large part for carbon storage/sequestration and, to some extent, for flood mitigation. In many sectors of society, these may take priority over any potential for recovering biodiversity, but if these species do benefit, this may be viewed as a fortunate added bonus.
Can we add in a reference to IUCN Briefings setting out restoration goals – including principle of stabilisation - http://www.iucn-uk-peatlandprogramme.org/sites/www.iucn-uk-peatlandprogramme.org/files/11%20Peatland%20Restoration_FINAL.pdf

1.3 Existing monitoring guidance

Appendix 1 shows a summary of existing monitoring guidance and considers the potential for two existing monitoring approaches ((Common Standards Monitoring (CSM) (JNCC 1998) and the 'trajectories approach' (Groom 2015)) to contribute to monitoring biodiversity responses to peatland restoration. In summary, whilst CSM is an adopted technique for assessing peatland condition, it is not designed to evaluate the effect of particular interventions. Furthermore, whilst the general principles of the trajectories approach underpin the Blanket Bog Restoration Strategy for England (Defra 2015) and the trajectories approach in simple form is being recommended by NE for monitoring the effect of restoration interventions under upland Long-Term Plans in England (D Glaves in litt.), it is not yet fully developed or adopted for blanket bog monitoring. Therefore, neither CSM nor the trajectories approach may currently provide the most appropriate frameworks for specifically monitoring biodiversity responses to restoration, and below we consider approaches that may allow more formal evaluation of restoration interventions.

1.4 Aims of this technical report

- Collate and review the range of biodiversity monitoring taking place across UK peatland restoration projects
- Review the evidence across temperate peatlands globally for biodiversity responses to peatland restoration
- Provide a critical review of whether current biodiversity monitoring is adequate to allow robust examination of responses to restoration. Where necessary, identify required improvements in monitoring (target taxa, methodologies, timescales)
- Develop guidance for future monitoring of biodiversity responses to restoration that will yield meaningful data

2. Collate and review the range of biodiversity monitoring taking place across UK peatland restoration projects

2.1 Methods

We created an electronic questionnaire to gather information on the range of monitoring currently undertaken at UK peatland restoration sites. This included questions about project size, aims of the restoration, budget and % spend on biodiversity monitoring, plus details on monitoring including taxa, methods, use of baselines and controls and timescales. As the focus was on biodiversity monitoring, we did not gather data on other monitoring (hydrology, carbon etc) as this would have increased the scope of the work considerably. The questionnaire was sent by email to 55+ contacts who were either attached to known restoration projects or otherwise involved in UK peatland restoration. These contacts were also asked to circulate among their networks and the questionnaire was also promoted on social media to increase the number of potential recipients. Nil returns (peatland restoration sites not undertaking biodiversity monitoring) were also encouraged. Key data were extracted from returned questionnaires and summarised.

2.2 Results and discussion

Twelve questionnaire returns were received. This represents a small sample (maximum 6%) of the 200+ peatland restoration projects in the UK (IUCN peatland Programme, unpublished data). We were aware of some other restoration projects that conduct biodiversity monitoring but who did not respond to the questionnaire, but the actual number of projects undertaking biodiversity monitoring in the UK is unknown.

Projects that responded comprised a range of peatland types, both upland and lowland (Table 1a) and some comprised multi-site restoration projects. There was considerable variation in the size (by land area) of these restoration projects and also their overall budgets, which ranged from £65,000 to £35 million, although budget will also be influenced by project duration.

Biodiversity was by far the most important stated objective for restoration, with projects attributing a mean importance score of 4.8 (out of maximum 5) to restoring biodiversity (Table 1a). This could of course be skewed if restoration projects with an interest in restoring biodiversity were more likely to respond to the questionnaire. The next highest-scoring restoration aim was restoring hydrological functioning (mean importance score 3.1, Table 1a).

Eleven of the responding sites undertake some form of biodiversity monitoring, with one project confirming that no biodiversity monitoring takes place (Table 1b). Funding allocated to biodiversity monitoring varied widely; of the five projects that reported their spend on biodiversity monitoring, this varied from £200 to £500,000 of total project budget (not per annum. spend). When expressed as a percentage of total project budget, spend on biodiversity monitoring ranged from 0.3 – 37.7% per project, with a median of 1.1% (Table 1b). However, spend at two of the projects is markedly higher than the remainder, at 37.7% and 5.0% of overall budget (next highest 1.1%). These two sites are both nature reserves managed by a large NGO dedicated to nature conservation. If these two sites are excluded, the remaining three projects spend between 0.3% and 1.1% of overall budget, mean 0.7%, on biodiversity monitoring. It should be noted that spend may not directly relate to overall monitoring effort; whilst some monitoring is conducted using dedicated monitoring staff (generally paid), volunteers are however the most common type of surveyor across all taxa (Table 1b).

Eleven projects reported that they monitor vegetation responses, 9 invertebrates, 9 birds, 4 mammals, 4 reptiles, 4 amphibians and 2 microbes (Table 1b). Most biodiversity monitoring is field-based, as might be expected, but three projects make use of remote sensing for vegetation monitoring. These same projects also undertake field monitoring of vegetation and calibration of the two methods would be beneficial, for informing these and other projects.

Within the broad taxonomic groups (vegetation, invertebrates etc), reported monitoring of individual taxa is highly variable across sites (Table 1b). Although the questionnaire did not gather information on motivations for monitoring individual species, variation between projects could conceivably be due to project or organisational preferences or priorities, opportunistic availability of suitably skilled staff, decisions to monitor species that are considered to be locally or nationally important and/or decisions to monitor particular flagship species, rather than, or in addition to, their pre-selection as measurable targets for peatland recovery. *Sphagnum* moss, restoration of which should be key in terms of restoring peat-forming processes (Rydin and Jeglum 2006), appears to be relatively well monitored, with monitoring taking place on 5/6 blanket bog projects and 3/4 lowland raised bog projects. However, at a finer taxonomic resolution, it cannot be ascertained exactly how many projects monitor individual *Sphagnum* species, which can be important for assessing environmental conditions on sites, as different *Sphagnum* species may be indicative of differing underlying conditions (Clymo 1973).

Among birds, some projects report standard ‘upland bird’ monitoring, with some also reporting monitoring individual species. Additional bespoke monitoring of individual upland species (ring ouzel *Turdus torquatus* and whinchat *Saxicola rubetra*) was undertaken within a single project each. These may be examples of species that may be important at a particular site, rather than representing measurable targets of restoration success per se. Great Bitterns *Botaurus stellaris* are monitored on 2/3 ‘fen, marsh, swamp’ sites, with the other site being well out of the bittern breeding range.

Monitoring frequency varies widely. Vegetation is reported as monitored anywhere from annually, every 5-6 years, to ad-hoc/occasional (Table 1b). Baseline vegetation monitoring, where conducted, took place anywhere between 1 and 5 years pre-restoration. Post-restoration monitoring timescales also vary. Invertebrates are most commonly monitored annually (5/9 projects). Birds are also most commonly monitored annually (6/9 projects) but at other sites bird monitoring is much more intermittent - up to every 10 years within one project. Monitoring of reptiles and amphibians is much patchier, with only 1/4 projects undertaking monitoring of each of these annually, with the other three projects undertaking ‘ad-hoc/occasional’ monitoring for each respectively. This could be of concern given the potential impact of some restoration work on different reptile life stages through disturbance and hence the need to monitor responses (ARG UK 2018). Within-season frequency of monitoring also varies widely across taxa and projects (Table 1b). Ad-hoc/occasional monitoring would understandably be expected to have the lowest value for assessing progress towards recovery.

The range of monitoring methods deployed is considerable. For example, some projects report vegetation monitoring using quadrats (of varying size) while others report using transects, although it should be noted that these are not mutually exclusive as quadrats may often be sited along transects. Birds are monitored using a variety of point counts and transects across sites, and in blocks or sites of widely varying size.

The overall study design applied to monitoring (use of baselines, post-restoration monitoring and controls) varies widely across taxa and projects (Table 1b). Use of baseline monitoring is reasonable although not universal; 8/11 sites report establishment of a pre-restoration baseline for vegetation, 3/9 invertebrates and 4/9 birds. A lack of baseline monitoring could potentially relate to short funding cycles, for example where capital restoration works need to be completed within a year’s funding and do not allow time for baseline data collection. Post-restoration monitoring is also variable, occurring at 9/11 sites for vegetation, 6/9 for invertebrates and 5/9 for birds (Table 1b). Use of control/reference plots not subject to restoration (which could be an impacted site with no restoration, or a non-impacted ‘intact’ or ‘pristine’ site, representing opposite ends of the restoration trajectory, or both) is also highly variable. Controls are included in monitoring at 7/11 sites for vegetation, 2/9 sites for invertebrates, 1/4 for both reptiles and amphibians and 2/9 for birds. Assessing the use of these approaches within individual projects allowed us to identify what monitoring takes place under various study designs (Table 2). BACI (Before-After-Control-Impact) designs should enable the most robust testing of biodiversity responses, as these use baselines and controls. Use of BACI designs is limited among the projects that responded to the questionnaire, with only four projects deploying this, all for vegetation monitoring. Control-Impact monitoring (no baseline but monitoring post-restoration in restored and control areas) was also formally undertaken at only four taxa/project combinations (Table 2). Before-After monitoring, lacking controls but using a baseline at restored areas, was deployed for six instances of monitoring. The generally low use of control sites could relate to controls not being considered when monitoring programmes were designed; local site conditions such that it is not possible to avoid re-wetting the whole of a site without engineering out sections (which may be highly undesirable); or funding conditions stipulating that all a site is restored. It may of course be possible to monitor off-site controls, although this could add to monitoring costs. Such factors could of course apply to all peatland monitoring, not just biodiversity responses. It could also point to wider issues, such that restoration funding schemes are designed without biodiversity evaluation as a recognised priority and without adequate scientific advice or scrutiny.

Most project respondents considered that monitoring methods had not changed substantially during the lifetime of the project. Changes in methods were considered to be most common for vegetation monitoring, with 4/11 sites having changed, but less frequent for other taxa e.g. invertebrates and birds both 1/9. The reasons for changes in methods are unknown but could relate to changes in personnel at a project.

Two sites reported limitations to doing more monitoring, one citing funding and one unspecified. However, we would be very surprised if funding is not a limitation at other sites. Insufficient monitoring could also relate to time pressures due to short funding cycles that only cover restoration work, or potentially issues relating to retention of experienced staff who can carry out survey work.

Reported motivations for undertaking monitoring are interesting. Perhaps surprisingly, only two projects are undertaking vegetation monitoring, and one undertaking mammal recording, because it is a requirement of the funding source. Thus, remarkably, we found only three examples where monitoring took place at the request of peatland restoration funders, and this might go a long way to explaining the lack of monitoring at some projects.

Chase up windfarm companies – perhaps Scottish Power

3. Review biodiversity responses to peatland restoration in the existing literature

3.1 Methods

We undertook a literature review to identify studies describing biodiversity responses to peatland restoration. Although this technical report relates to biodiversity monitoring at UK peatland restoration sites, for the literature review we broadened the scope to include temperate peatlands globally, to increase the likely sample size of studies. The review was primarily aimed at the peer-reviewed, published literature but we also incorporated unpublished/grey literature where available to us, as described below. Following previous approaches for systematic reviews (Pullin and Stewart 2004), we first identified the question of interest: “How does biodiversity respond to peatland restoration?”. We then identified our search terms, which described i) taxa of interest, either biological groups or wider terms relating to habitat; ii) terms describing a range of restoration interventions combined with terms describing the main peatland systems to which restoration has been applied.

A search was then performed in Web of Science (WoS), combining all terms. The search was restricted to "articles", "early access", "letters", "proceedings papers" and "reviews", in English language, and excluded papers from tropical areas using “NOT TS=(”tropical”)”. The search terms were run through WoS twice, once searching for their appearance in topic (TS) and once searching for their appearance in the title (TI). Results from the two searches were then combined in WoS. Our aim is to publish the review in the peer-reviewed literature and this will include a full reproducible methodology.

The 822 documents identified were then subjected to an initial filtering exercise. The aim was to remove documents that did not specifically address peatland address restoration. This was done in three hierarchical stages; if the title indicated a document was unsuitable as there was reference to peatland restoration, it was removed without further review; if unclear from the title then the abstract was read; if still unclear then the main text was skim-read. Documents were also excluded if they were not relevant to peat-dominated habitats (i.e. wetlands that were not obviously peatlands were excluded), did not address clear biodiversity responses, compared only degraded (unrestored) versus pristine sites or addressed only passive or spontaneous recovery in the absence of active restoration. Whilst passive/spontaneous recovery could be considered a form of restoration we do not include it here, particularly as the focus of the review was on active restoration and our search terms were designed to identify documents describing such studies.

In a second stage of prioritisation, the remaining 274 documents were allocated by DD to two ‘tiers’: tier 1 (clearly of use, being a quantitative study of biodiversity responses to peatland restoration, or a review of the topic); tier 2 (less clearly of use, for example biodiversity only dealt with tangentially with the focus more on water/carbon/gases). This stage yielded 197 tier 1 documents.

We then added grey literature or theses (31 documents) that we were aware of from restoration projects, mainly from the UK but incorporating studies from other temperate peatland zones where appropriate. Although addition of grey literature could not be done in a systematic manner it was still considered appropriate to include relevant studies that we had become aware of. After assessment, all grey literature was assigned directly to tier 1.

Checking of the initial filtering was conducted by dividing the 822 documents into four batches of 165 documents and one batch of 162. These were randomly allocated to four observers, with one observer checking two batches and the other three observers checking a batch each. This yielded 43 papers that DD had not selected. These 43 were then allocated to tier 1 and 2 by DD, yielding three additional papers in tier 1.

The remaining 231 documents were prioritised to include only primary, quantitative studies of restoration, excluding some additional studies that addressed only passive/spontaneous recovery and which hadn’t been excluded earlier. Reviews were removed at this stage but were first read to extract any further primary studies that had been missed by the initial searches. Also at this stage, if any documents duplicated the same study (for example a thesis and subsequent peer-reviewed paper), the paper that had been through peer review was retained. This stage yielded a final group of 179 documents. This was an unexpectedly large number, and a full review of all documents was not feasible within the available timeframe. Therefore, for the purposes of this report, we reviewed the following groups and summarised what the literature tells us about their responses to peatland restoration: birds, microbes, craneflies, amphibians and mammals. The intention is to conduct a full review including vegetation and non-cranefly invertebrates for a peer-reviewed paper.

3.2 Results and discussion

3.2.1 General findings

Among the 179 documents, the representation of different taxa was as follows, with some studies addressing multiple taxa; vegetation 144 documents (80.4%), invertebrates 33 (18.4%), microbes 14 (7.8%), birds 6 (3.4%), amphibians 1 (0.6%), mammals 2 (1.1%), reptiles 0.

This suggests that the evidence base is most extensive for assessing vegetation responses to peatland restoration, with a more limited evidence base for invertebrates and microbes and very little currently available evidence for birds, amphibians, reptiles and mammals.

3.2.2 Responses of birds to peatland restoration

The literature search identified only six studies which in some way linked bird population responses to ecological restoration of peatlands (Mazerolle et al 2006; Sills & Hirons 2011; Calladine et al 2014; Görn et al 2015; Wilkinson and Douglas 2015; Hughes 2018).

Of these studies, two are narrative accounts of the reconversion of fen peatlands previously converted to arable agriculture (Lakenheath, UK – Sills and Hirons 2011) or subject to commercial peat extraction (Ham Wall, Somerset, UK – Hughes 2018) to wetland nature reserves, and the bird communities that have become established there. Over a period of roughly 15 years, both of these studies show establishment of diverse wetland habitats including open waters, wet woodlands, grasslands and, especially, *Phragmites* reed-beds. This is accompanied by establishment of breeding populations of a wide range of wetland breeding birds of high conservation concern such as Eurasian Bittern *Botaurus stellaris*, Great Egret *Ardea alba*, Little Bittern *Ixobrychus minutus*, Western Marsh Harrier *Circus aeruginosus*, Garganey *Spatula querquedula*, Bearded Reedling *Panurus biarmicus*, Northern Lapwing *Vanellus vanellus* and Common Crane *Grus grus*, plus large populations of commoner reed-bed species such as Eurasian Reed Warbler *Acrocephalus scirpaceus*, Common Reed Bunting *Emberiza schoeniclus* and Cetti's Warbler *Cettia cetti*.

The third study (Görn et al 2015), which also focused on fen peatlands, in this case in Germany, compared breeding bird responses in four categories of paludicultural restoration of peatlands (moist grassland cut for hay, summer-cut reed-beds, winter-cut reed-beds and unmanaged wetland habitat dominated by reed-beds) previously converted to intensive agriculture, with control areas which remained under intensive grassland management for multiple silage cuts. Over 19 years post-intervention, bird species richness and alpha-diversity was significantly higher (in the range 2-6-fold) on the restoration management types than on the unrestored silage meadows. A bird conservation value index which considered conservation status at local, regional/national and international scales was significantly higher in summer-harvested paludicultural sites than other management regimes (and essentially zero in intensive silage meadows). This conservation index result was heavily influenced by the high abundance of Common Snipe *Gallinago gallinago* and Northern Lapwing in summer-harvested sites, both of which had high conservation value scores at regional and national level.

A fourth study (Calladine et al 2014) measured breeding bird abundances on Scottish blanket bog subject to vegetation management measures (reduced grazing, drain blocking and targeted vegetation cutting) designed to compensate for effects on bird populations of loss of habitat to nearby coal-mining activity. These data were compared to data from nearby, intact blanket bog. However, no significant vegetation effects and hence no substantive response from bird populations was detected over a nine-year period.

None of the above studies involved restoration activity that was specifically designed as a restoration of an ecologically functional fen or blanket bog peatland: three focused primarily on wetland habitat creation and one on vegetation management measures designed to benefit bird populations in compensation for loss of habitat elsewhere. Only two studies have focused on bird population responses to peatland restoration activity designed primarily to re-establish functioning peatlands. These both focus on blanket bog peatlands and are also the only studies to feature a full before-after-control-intervention (BACI) design. However, the first of these (Mazerolle et al 2006) was scaled and replicated primarily to study the effects on vegetation and arthropod communities of creation of bog pools, as a component of restoration of a blanket bog subjected to peat extraction. Breeding bird monitoring involved no replication between the restored bog and a pristine comparison site, although there was an informal indication in the data that songbird species richness in the small restored area had increased to a higher proportion of the richness in the control area by four years post-restoration.

This leaves the unpublished study by Wilkinson and Douglas (2015) on two degraded blanket bog landscapes in northern England as the only well-replicated BACI study of breeding bird responses to peatland restoration. The primary aim was to restore active blanket bog function in areas suffering severe peat erosion following decades of heavy agricultural grazing and burning combined with the impacts of atmospheric pollution and acidification of rainfall during the 20th century, and thus to reduce erosive peat loss to watercourses and costly discolouration of drinking water supplies. Measures implemented included grazing reduction, drain blocking, bog vegetation inoculation, conifer tree removal, native woodland planting and wetland scrape creation. Monitoring was conducted over a nine-year period, across 83 surveyed 1-km squares in two separate areas, and yielded sufficient data for analyses for 18 bird species. Restoration measures were associated with consistently positive population responses for five species (European Golden Plover *Pluvialis apricaria*, Dunlin *Calidris alpina*, Eurasian Curlew *Numenius arquata*, Skylark *Alauda arvensis* and Dipper *Cinclus cinclus*) and consistently negative effects for only one (Meadow Pipit *Anthus pratensis*). Dipper response was associated with the overall package of restoration measures; management to raise water tables was associated with positive responses by Golden Plover, Curlew and Skylark (Figs 1-3), whilst bare peat revegetation was associated with positive responses by Dunlin (Fig. 4) and Curlew (Fig. 2) and a negative response by Meadow Pipit (Fig. 5).

Overall, these studies show that rigorous assessments of breeding bird population and community responses to restoration designed to recover peatland function are extremely rare; only one (Wilkinson and Douglas 2015) has a full BACI design. However, this and some (but not all) of the other five less rigorous and or bird-targeted studies available suggest that bird population responses may be dramatic and rapid, with marked species abundance responses within 10 years and transformation of breeding bird communities in less than 20 years, in cases where restoration is associated with change of land use. Very often, bird responses include increases in species of high conservation concern, especially those associated with wetlands (Sills and Hirons 2011; Görn et al 2015; Hughes 2018), which are habitats that have suffered a high degree of conversion and fragmentation by agriculture and other factors including urban development (Asselen et al 2013). The only exception was the study of Calladine et al (2014) where interventions failed to affect vegetation structure and composition over approximately a decade, and thus it is perhaps little surprise that responses of bird populations were minimal.

3.2.3 Responses of microbes to peatland restoration

We found 14 studies which investigated the response of microbes to peatland restoration, half of them published within the last three years (Croft et al 2001; Andersen et al 2006; Watts et al 2008; Andersen et al 2010; Juotonen et al 2012; Basiliko et al 2013; Elliott et al 2015; Secco et al 2016; Swindles et al 2016; Ballantine et al 2017; Creevy et al 2018; Putkinen et al 2018; Reumer et al 2018; Urbanova et al 2018). All but one of the studies (Watts et al 2008) are from North America or Europe. The commonest impacts studied were restoration following either peat mining or drainage intended to increase the silvicultural or agricultural production from peatland vegetation.

Most studies took a carefully-designed observational or correlative approach, selecting pre-existing study sites, taken to represent peatlands that were (i) impacted and unrestored; (ii) undergoing restoration management; and (iii) intact (or ‘pristine’ or ‘natural’). This approach had the advantage of allowing researchers to investigate sites that had been undergoing restoration or recovery for many years (the oldest sites ranging from 3 to 63 years since restoration or recovery commenced; median 14 years). However, interpretation of these studies is complicated by the possibility that different types of peatland sites may have been chosen in the past for exploitation, restoration or to be left intact. Some studies also included abandoned, impacted sites, where no restoration management was taking place, to investigate the process of spontaneous recovery (Basiliko et al 2013; Elliott et al 2015; Ballantine et al 2017; Putkinen et al 2018). In addition to these observational studies, we found two experimental studies (Watts et al 2008; Swindles et al 2016), where the researchers put in place alternative restoration treatments, allocated at random to potential sites, and then compared outcomes. These experimental studies were necessarily shorter in timescale (including 1-2 years after restoration).

In terms of the microbial groups studied, three studies focussed on testate amoebae and their community responses (Swindles et al 2016; Secco et al 2016; Creevy et al 2018). The remaining studies covered broader groups of microbes, measuring either biomass or function (five studies); community responses (two studies) or both (four studies).

Only one study found no clear response to restoration by the microbes studied (Andersen et al 2010). However, the authors considered that this may have been partly due to the method used to characterise microbe communities (phospholipid fatty acids); they recommended molecular methods as likely to be more powerful, and such approaches are now commonly used in more recent studies.

In four studies, microbial responses to peatland restoration could be described as 'inconsistent', with some microbial groups or indices showing a response, and some not. Andersen et al (2006) found that estimates of microbial biomass in restoration areas were intermediate between impacted and natural sites when estimated with one technique, but not another. Basiliko et al (2013) found that peat mining and subsequent restoration affected overall microbial activity, with, for example, microbial CO_2 production in restoration areas being similar or exceeding that of natural sites, and several times higher than mined or abandoned sites. However, microbial community structure showed little relationship with the restoration trajectory, being more influenced by location and peat properties. Juottonen et al (2012), studying methane-cycling microbes in forestry-drained peatlands, found that areas undergoing restoration for 10-12 years had a similar community composition to natural sites, but lower abundance; consequently, methane production in restoration areas remained similar to that of impacted areas. Urbanova et al (2018) found that microbial biomass in restoration areas became similar to that of natural sites after 6-15 years, but only in their bog study sites, not in their spruce-swamp study sites.

In all the remaining nine studies (Croft et al 2001; Watts et al 2008; Elliott et al 2015; Secco et al 2016; Swindles et al 2016; Ballantine et al 2017; Creevy et al 2018; Putkinen et al 2018; Reumer et al 2018), microbial indicators showed positive responses to peatland restoration, varying from modest, to mainly complete, over the (1-63 year) timescale of these studies. Reumer et al (2018) highlighted the rapid response by microbial indicators, compared to that of plants, in the initial years following restoration management. A similarly rapid (within two years) response was also shown by microbes during the two experimental studies (Swindles et al 2018; Watts et al 2008), allowing them to compare biological responses to different restoration management options within a short time frame. Meanwhile, two relatively long-term studies found only modest recovery (Creevy et al 2018 – 17 years) or incomplete recovery (Elliott et al 2015 – 25 years) suggesting that full microbial recovery can sometimes be slow, supporting an estimate of around 50 years suggested by Ballantine et al (2017). However, three other studies reported mainly complete recovery by indicators of microbial abundance or function over shorter timescales of 10-17 years (Putkinen et al 2018; Secco et al 2018; Reumer et al 2018), although in the last two studies, some differences in community composition remained.

In conclusion, microbial responses to peatland restoration are commonly positive - within just a few years, there are often clearly detectable changes in microbial function and/or community composition towards that of more natural sites. Some studies have found mainly complete recovery of microbial function within 20 years. However, this has been found to vary between different site types or groups of microbes, and full recovery of community composition appears to be a generally slower process.

3.2.4 Responses of craneflies to peatland restoration

Craneflies (Tipulidae) are a key component of peatland biological communities, being important herbivores and a major prey item for other taxa such as birds (Pearce-Higgins 2010). They are also susceptible to drought (Carroll et al 2011) and could therefore be considered an important keystone group in terms of indicating peatland recovery such as water table.

Four studies assessed cranefly responses to peatland restoration, two on blanket bog, in the UK (Carroll et al 2011) and Ireland (Hannigan et al 2011), and two on mires in Finland (Ilmonen et al 2013; Noreika et al 2015). Hannigan et al (2011) and Ilmonen et al (2013) provided only incidental records of Tipulids in relation to restoration and are not considered further here.

The two blanket bog studies deployed Impact-Gradient designs, although in one study (Carroll et al 2011) the control sites were unrestored areas and in the other (Hannigan et al 2011) these were intact areas more akin to restoration target/reference areas. Carroll et al (2011) sampled craneflies over two years at blocked and unblocked drains on three blanket bog sites. Soil moisture was also monitored to help assess recovery of the bog and aid interpretation of cranefly responses. Treatment drains had been blocked 2-4 years previously. Cranefly abundance increased with increasing mean soil moisture (Fig. 6). In both years, the relationship was such that cranefly abundances were low at relatively dry sites but could be high or low at relatively wet sites. Analyses found that, overall, cranefly abundance was significantly and positively related to soil moisture in both years. Soil moisture was increased where drains were blocked (Fig. 7). Responses of cranefly abundance to drain blocking were only statistically significant in one of the two years; 2010 (Fig. 8). In this year there was significantly higher cranefly abundance at blocked drains, with an overall mean of 5.30 per sample at blocked drains and 1.17 per sample at unblocked drains, representing a 4.5-fold difference in density. In 2009, the results were in the same direction as those from 2010, but the effect was much weaker. The study found rapid responses (within only 2-4 years following drain blocking) of both soil moisture and craneflies to restoration and concluded that the benefits of restoring ecosystem moisture levels are likely to be greatest during dry years and at dry sites, showing that peatland restoration can potentially reduce some of the negative effects of climate change on vulnerable peatland systems.

Noreika et al (2015) studied responses to drainage of pine mire in Finland. Restoration was performed by filling in ditches to raise the water table and cutting trees to mimic the natural tree stand structure of mires. Most study areas contained a drained, restored and pristine treatment, allowing Impact-Gradient comparisons. Craneflies were sampled 1-4 years following restoration. Thirty-four cranefly species were collected, of which nine were classified as mire specialists, five of which were considered sufficiently abundant for individual analyses. Three of these five cranefly species were more numerous in the restored than drained treatment, and most abundant in the pristine treatment. One species was more abundant in the restored than the drained and intact treatments. One species showed no response to restoration, with abundance comparable between drained and restored areas, with both of these lower than pristine areas. Among forest generalist species, one was positively associated with restored sites, being least abundant in the drained treatment; one was most abundant in the pristine treatment, less abundant in the restored, and least abundant in the drained treatment. Responses of craneflies to the specific vegetation restoration measures were also assessed. Three of the five mire specialist species showed positive responses to *Sphagnum* cover, while two did not, whilst one forest generalist responded positively to *Sphagnum* cover and one did not. Mire specialists generally responded negatively to tall tree cover (three of five species) or only weakly positively (two species), while the two forest generalist species showed stronger positive associations with tall tree cover.

In summary, the two studies that analysed cranefly responses in detail (Carroll et al 2011; Noreika et al 2015) found that craneflies can respond positively, and rapidly (within 1-4 years) to restoration. Specifically, increases were associated with measures to raise water levels and/or increase soil moisture, and increases in some peatland specialist species were associated with measures of other peatland indicators such as *Sphagnum* cover.

3.2.5 Responses of amphibians to peatland restoration

In the single study identified, Mazerolle et al (2006) found that, overall, amphibians (tadpoles) were more likely to occur in man-made pools created as part of restoration of a formerly mined peatland, than natural pools in undisturbed peatland. This was considered likely to be because the man-made pools were still on a trajectory towards natural bog pools during the study. In particular, the man-made pools were more alkaline than bog pools, with acidity known to limit amphibian distribution. There was, however, variation in amphibian species composition between natural bog pools and man-made pools. American toads *Bufo americanus* first colonised the man-made pools, whereas they were absent from natural bog pools. In addition, no leopard frog species occurred at the restored site after 4 years, whereas they were frequent in natural bog pools.

3.2.6 Responses of mammals to peatland restoration

Two studies were identified. In a narrative study, occupancy of a fen wetland restored from agricultural land by water vole *Arvicola amphibius* and otter *Lutra lutra* is reported to have taken place (Sills and Hirons 2011) but no further quantitative responses are reported. Gilbert (2013) compared deer abundances (red and roe deer combined) on intact blanket bog, afforested bog and formerly afforested (now felled) bog. Changes over time were not examined but the deer abundance index was lowest on intact bog. Whilst this could suggest that restoration of afforested bog may not be expected to lead to increases in deer, responses in deer abundance to bog restoration may also depend on other factors such as the presence or not of fencing, deer species and region of the UK, and these may need to be examined further to draw meaningful conclusions about deer responses to peatland restoration.

4. Provide a critique of whether current biodiversity monitoring is adequate to allow robust examination of responses to restoration. Where necessary, identify required improvements in monitoring (target taxa, methodologies, timescales)

4.1 Is current UK peatland monitoring sufficient to enable biodiversity responses to be robustly tested and reported?

4.1.2 Study design

Based on responses to our questionnaire (see 2.2), BACI studies are rarely applied at UK peatland restoration sites (Table 2). BACI designs are expected to provide the most robust studies, as biodiversity responses to restoration can be tested on areas subject to restoration, both before and after restoration is applied, and against unrestored controls or intact areas (ideally both, in which case the extent of progress on restored sites can be compared to unrestored and fully restored over the same timescales). However, Control-Impact (CI, testing only post-restoration responses on restored and unrestored/intact sites, and Before-After designs (BA, pre- and post-restoration monitoring on restored areas, with no controls), could both yield meaningful data. Four CI and 6 BA studies are deployed. The remainder of monitoring is unlikely to enable any formal testing, as it is not supported by pre-restoration data and/or controls.

There are a number of implications of the lack of robust monitoring designs. Clearly, we are missing opportunities to test and demonstrate biodiversity responses to restoration. Any post-restoration monitoring that is not supported by at least one of a pre-restoration baseline or controls (therefore not conforming to BACI, CI or BA designs) is unlikely to be a good use of often limited resources. In addition, if restoration trajectories do not progress as expected, these may not be detected at an early stage, limiting the ability to apply adaptive management principles and deploy (and test) remedial action. Furthermore, subsequent restorations may continue to be implemented ineffectively or at best sub-optimally. An example of the value of assessing responses periodically during restoration is the study of Hancock et al (2018). Monitoring revealed that progress of vegetation towards restoration outcomes had stalled at some parts of a site. This informed the roll-out of additional management and responses are being monitored. An important conclusion was that long-term vegetation monitoring has helped to identify barriers to recovery and the management needed to overcome them.

Other implications of a lack of robust monitoring include governments being unable to report on success towards achieving biodiversity restoration goals under the Aichi targets. Using Scotland as an example, high quality monitoring of biodiversity responses to peatland restoration could make a meaningful contribution towards assessing progress on a number of Aichi Targets including A1, A2, A3, B5, B10, D15 and E19 (SNH 2018b).

Add in discussion from IUCN briefings on biodiversity and definitions explaining what needs to be done in describing the control sites and state of peatland. NB include consideration of Sphagnum tope – structure etc – not just species.

http://www.iucn-uk-peatlandprogramme.org/sites/www.iucn-uk-peatlandprogramme.org/files/2%20Biodiversity%20final%20-%205th%20November%202014.pdf

http://www.iucn-uk-peatlandprogramme.org/sites/www.iucn-uk-peatlandprogramme.org/files/1%20Definitions%20final%20-%205th%20November%202014.pdf

4.1.3 How well are measurable biodiversity restoration targets monitored?

Sphagnum are a key peat-forming plant (Rydin and Jeglum 2006) and should be a key component of monitoring restoration targets. *Sphagnum* is reported as currently monitored at 5/6 blanket bog sites and 3/4 lowland raised bog sites. However, the extent to which different *Sphagnum* species are monitored and the use of baselines and controls for these is unclear. Therefore, we cannot conclude that the key biodiversity measure for assessing peatland restoration is currently being adequately monitored. Similarly, the extent of current monitoring of other important taxa such as craneflies, which may indicate peatland recovery through their association with soil moisture and are also important prey for groups such as birds, is also unclear. Much additional biodiversity monitoring focuses on groups which, whilst monitoring may be justifiable for reasons of local, organisational or conservation value, may not necessarily act as measurable biodiversity restoration targets.

4.1.4 Are standardised, recommended methods for each taxa being used across sites?

There is considerable variation in the methods currently being deployed. This is particularly apparent among vegetation, invertebrates and birds, where a range of sample units are used within each group. Where sample unit differs, for example variation in quadrat size, or use of quadrats on one site and transects at another, this could lead to inconsistent data collection and inability to compare responses between sites. This must be addressed in future monitoring (see below). The variation in approaches across sites suggests that monitoring protocols have largely been designed and implemented on a site-by-site basis. This is perhaps not surprising, as many peatland restoration projects operate more-or-less independently and there is currently no requirement to standardise methods or follow agreed protocols, although we suggest below how this could be addressed.

4.1.5 Is repeat monitoring being conducted at appropriate timescales?

Again, this is highly variable across sites and only one site reports monitoring vegetation at 25 years post-restoration, at 1-2 year intervals. Whilst this provides encouragement that some long-term monitoring is taking place, this is clearly an insufficient number of sites. There is a potential risk that frequent vegetation monitoring (e.g. 1 or 2-year intervals) could lead to trampling impacts, and such frequent intervals may not be necessary for assessing (sometimes slow) vegetation responses over the longer term. There is therefore an argument for conducting vegetation monitoring at less frequent intervals, but over the longer-term, using replicable methods. Other groups such as invertebrates or birds may show stronger year-to-year variation, so annual surveys may be more valuable to capture such variation and test whether longer-term trends exceed them.

4.1.6 If investment in monitoring differs between projects, why is this the case?

What is clear is that, away from nature reserves, the proportion of total project budget allocated to biodiversity monitoring is small, averaging 0.7%. The low percentage spend on biodiversity monitoring could reflect decisions taken to allocate as much money as possible to the capital cost of restoration work, to maximise the area that the funder believes may become restored. Whilst this is entirely understandable, this could come at a cost of adequate monitoring to understand whether the resources invested are delivering the desired outcomes.

A key issue for investment in monitoring is identifying at an early stage why the monitoring is needed at each site. Variation between sites may relate to the lack of an agreed rationale for what monitoring is seeking to achieve. Such a rationale could then be reflected in appropriately scaled funding of biodiversity monitoring activity as a critical component of peatland restoration funding. At sites where the interventions are particularly challenging or novel, then monitoring will be needed to test whether the restoration works, quantify any benefits and perhaps to adjust via adaptive management i.e. there is a scientific need for the monitoring. At sites deploying a limited or more typical suite of restoration measures, where the cause-effect relationship of biodiversity responses may be more well established, monitoring may still be needed to quantify a public benefit the for the resource invested i.e. a greater policy/legislative need for the monitoring. If the restoration intervention/s are well understood scientifically, for example with previously demonstrated and consistent results, and the benefits well accepted, then there may be no need to monitor at all. Consideration of the monitoring needs at each site will enable the investment in monitoring to be designed accordingly.

5. Develop guidance for future monitoring of biodiversity responses to restoration that will yield analysable data

The monitoring of biodiversity responses across peatland restoration projects in the UK should adopt a robust, standardised approach. Future developments could make better use of an internationally recognised framework, such as that advocated by the Conservation Measures Partnership (CMP) (Conservation Measures Partnership 2013): "The Open Standards for the Practice of Conservation [developed by the CMP] help teams be systematic about planning, implementing, and monitoring their conservation initiatives so they can learn what works, what does not work, and why — and ultimately adapt and improve their efforts." A standardised approach will enable biodiversity responses to be tested and guide future peatland restoration or management at the same sites and elsewhere. An adaptive management framework which enables responses to be assessed periodically, with restoration interventions adjusted if necessary, and sharing of monitoring results among restoration community are also key issues to address.

Our recommendations are:

(i) A network of sites deploying exemplar, standardised monitoring should be developed. This could follow the principles of the UK Environmental Change Network (http://www.ecn.ac.uk/). Sites in this network should not necessarily be sites that are all exemplars in terms of responses to restoration, as it would be useful for standardised monitoring to be deployed across sites with a range of conditions. Significant funding for capital works and monitoring should be made available, with peatland restoration projects bidding to become part of this network. Exemplar sites would be required to monitor biodiversity responses using agreed methods and periodically report their findings. This network should be supplemented by a much larger sample of representative peatland sites, where a more limited suite of monitoring, but still deploying consistent approaches, is adopted.

(ii) BACI designs are used wherever possible, to enable the most robust assessment of biodiversity responses. Where this is not possible either of the following two designs should be applied as a minimum: (a) Control-Impact designs, with control sites that include both unrestored and intact sites (accepting that pristine may be hard to identify); (b) Before-After designs, with a minimum of one-year baseline monitoring at sites to be restored, and ideally more years for taxa that can be more variable between years. For all designs, greater replication will add value, but single replicate case studies are also valuable to carry out and report. If standard approaches are used across sites, then multiple single-site case studies could ultimately be analysed together in meta-analyses.

(iii) Taxa monitored should enable measurable biodiversity restoration targets to be assessed. As a minimum, this should include *Sphagnum*, ideally to species level, plus additional taxa such as craneflies. The potential for birds to respond to restoration, shown in the literature as sometimes marked and rapid responses, suggests that monitoring of breeding bird responses could also be considered as an additional aspect of evaluating peatland restoration interventions.

(iv) Consistent methods are used for individual taxa, both within a site over time and across different sites. Where this requires the cessation of a particular technique and adoption of a new (different) technique to ensure standardisation, monitoring could, if necessary, be deployed using both techniques overlapping for an appropriate period, to enable calibration of the two approaches.

(v) Monitoring continues over a sufficient timescale to assess responses. It is critical that the long-term nature of peatland restoration is recognised in the development of monitoring programmes and that provision is made for this in organisational and programme budgets and plans. For example, it has been estimated (at lowland peatlands in Canada) that a significant number of characteristic bog (plant) species can be established in 3–5 years, a stable high water-table in about a decade, and a functional ecosystem that accumulates peat in perhaps 30 years (Gorham and Rochefort 2003). These timescales may be longer for higher-altitude UK upland systems with different climatic conditions. Over longer timescales, monitoring need not be annual but could for example be conducted at 2, 5, 10 20 and 30+ years post-restoration.

(vi) Progress towards recovery outcomes is assessed, using on-site monitoring data, at regular intervals, say every 5-10 years. This will enable remedial works to be deployed if restoration is not progressing as expected, using an adaptive management approach.

(vii) Consider more co-ordinated use of citizen science/volunteers (see for example (http://www.moorsforthefuture.org.uk/community-science). Whilst this example is aimed primarily at recording evidence of the impact of climate change on blanket bog, some of the indices measured (e.g. changes in *Sphagnum* and other vegetation and water table depth) are consistent with those recorded to assess biodiversity responses to restoration.

(viii) Explore greater use of remote sensing and other technological solutions (e.g. drone photography of vegetation and associated image analysis), along with ground-truthed data, to monitor aspects of biodiversity responses, in particular vegetation (see Williamson et al 2017).

(ix) Data are shared to enable collaborative meta-analyses of biodiversity responses to be undertaken.

(x) Biodiversity monitoring at UK peatland restoration sites is co-ordinated by a single body, for example the IUCN Peatland Programme, at least at exemplar sites, to ensure consistency in approach, with this organisation also receiving and storing monitoring data.

These recommendations are summarised in a schematic diagram showing how a standardised approach to biodiversity monitoring could operate (Appendix 2).

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Table 1. Summary of questionnaire responses describing biodiversity monitoring taking place at UK peatland restoration projects. Twelve responses were received including one nil return (no monitoring undertaken). Unless otherwise stated, responses are presented as number of sites. Note for some questions the number of responses does not necessarily correspond with number of sites undertaking monitoring per taxa, due to nil responses or multiple methods per taxa

(a) Site details

What is the conservation status of your site?	**None**	**SSSI**	**SAC**	**SPA**	**National Park**	**Nat. reserve**	**AONB**	**NNR**	**Other**		**Responses**
	1	11	10	5	2	2	2	1 (part-of)	2		12
Which vegetation type/s are present on the site?	**Blanket bog**	**Upland heathland**	**Fen**	**Lowland heathland**	**Lowland raised bog**	**Fen/marsh swamp**	**Other**				12
	6	4	2	0	4	3					
How many staff are working on your project (full-time equivalent)?	mean 4.4; min 0; max 32										12
What is the total project budget (£)?	mean 6.8 million; min 65,265; max 35 million										8
Funding source for restoration?	**Env. Stewardship**	**ESA**	**CSS**	**EN wildlife enhancement**	**Grants - local**	**Grants - regional**	**Grants - national**	**Grants - intern'l**	**Private sector**	**Other**	
	5	1	1	0	4	8	9	6	4	3	12
Size of project area (sometimes a collection of multiple sites) (ha)?	mean 12,770; min 60; max 65,000										7
Size of project site (ha)?	mean 3542	min 130	max 20,000								7
Justification for undertaking project (0 low importance to 5 high importance)?	**Carbon**	**Biodiversity**	**Culture/ recreation**	**Hydrology - function**	**Hydrology - water quality**	**Other**					12
Mean score across responses	2.8	4.8	2.2	3.1	2.7	1					
Briefly, can you outline your main objectives for restoration?	6 out of 11 (55%) projects mention biodiversity benefits among main aims										11

(b) Biodiversity monitoring

	Vegetation	Inverts	Reptiles	Amphibians	Birds	Mammals	Microbes	Responses
No. sites undertaking biodiversity monitoring?	11	9	4	4	9	4	1	12
Spend on biodiversity monitoring (all taxa) (£)?	mean 203,000; min 200; max c500,000							5
As a % of overall project budget?	mean 8.9; min 0.3; max 37.7; excluding two highest spenders (both nature reserves), range of remainder 0.3 to 1.1, mean 0.67%							5
Monitoring field based (f), remotely sensed (r) or both (b)?	3b, 8f	9f	4f	4f	9f	4f	2f	
Number of sites monitoring different taxa?	bryophytes (6)	butterflies (4)	adders (1)	toad (1)	bittern (2)	deer (1)		
	Sphagnum (5)	moths (2)	lizards (2)		'upland' birds (3)	Mt. hare (1)		
	vasc. plants (5)	aquatic (1)			whinchat (1)	mink (1)		
	NVC (3)	damselfly (1)			ring ouzel (1)	otter (1)		
	SCM (2)	beetle (2)				water vole (1)		

How frequent is biodiversity monitoring?	**Vegetation**	**Inverts**	**Reptiles**	**Amphibians**	**Birds**	**Mammals**	**Microbes**	**Responses**
Annually	3	5	1	1	6	3		12
1-2 years	3							
3 years	1							
3-4 years	1							
5-6 years	3	2			1			
10 years					1			
Ad-hoc	1	2	3	3	1	1	1	

In years conducted, what is within-season frequency?	**Vegetation**	**Inverts**	**Reptiles**	**Amphibians**	**Birds**	**Mammals**	**Micro-orgs**	**Responses**
Weekly		3			2			11
Fortnightly		1	1	1	1	1		
Monthly		1			1	1		
Once	9				1			
1-2 visits					1	1		
1-4 visits		1						
3 visits					2			
5 visits					1			
10 visits		1						
Ad-hoc		2	1	1	1	1	1	

Table 1b continued

What are the sample units?	**Vegetation**	**Inverts**	**Reptiles**	**Amphibians**	**Birds**	**Mammals**	**Micro-orgs**	**Responses**
1m x 1m quadrats	4	1						10
2m x 2m quadrats	4							
Individual traps		1						
Spot samples		1	1	1	1	1		
Point counts					1			
Transects 1km		1			1			
Transects (unspecified length)	2	1			2	1		
Individual 'sites'	1	1			1	1	1	
Plots 2km²					1			
6-10 km² blocks					1			

Who does the monitoring?	**Vegetation**	**Inverts**	**Reptiles**	**Amphibians**	**Birds**	**Mammals**	**Microbes**	**Responses**
In-House Project Officer	3	2		1	1	2	1	12
In-House (dedicated) Monitoring Officer	5	1			2	1	1	
In-house (other)	3	1			3	1	1	
Academic collaboration (not paid by project)	3	1			1		1	
Academic contractor (paid by project)	1							
Private contractor/consultant (paid by project)	2	1			1			
Volunteers	6	9	4	4	8	5	1	
Utilising citizen science	1	1	1	1	1	1		
Pre-restoration baseline monitoring?	8	3	3	1	4	1	0	12

If yes to above, how many years baseline monitoring?	**Vegetation**	**Inverts**	**Reptiles**	**Amphibians**	**Birds**	**Mammals**	**Micro-orgs**	**Responses**
1	2							9
1-2	1							
2	3				2			
1-5	1	1			1	1		
2-4	1							
Monitoring during restoration?	4	4	1	1	4	2	1	

If yes to above, how many years during restoration?	**Vegetation**	**Inverts**	**Reptiles**	**Amphibians**	**Birds**	**Mammals**	**Micro-orgs**	**Responses**
1		1						6
1-20	1	1			1	1	1	
4	1							
8	1				1			
24					1			
25	1							
Monitoring post-restoration?	9	6	3	2	5	3	1	12

Table 1b continued

If yes to above, how many years post-restoration?	**Vegetation**	**Inverts**	**Reptiles**	**Amphibians**	**Birds**	**Mammals**	**Micro-orgs**	**Responses**
1	1	1						7
2	1	1						
1-20					1			
2-10	1							
3-20	1							
8	1				1			
12	1							
25	1							
Does monitoring include control plots?	7	2	1	1	2	2	1	12
Do control plots use same monitoring methods?	7	2	1	1	2	2	1	12
If using controls, how many plots?	**Vegetation**	**Inverts**	**Reptiles**	**Amphibians**	**Birds**	**Mammals**	**Micro-orgs**	**Responses**
5	2							6
2-6	1							
6	1							
10	1							
27		1						
284	1							
Various per site			1	1	1	1		
	Vegetation	**Inverts**	**Reptiles**	**Amphibians**	**Birds**	**Mammals**	**Micro-orgs**	**Responses**
Have survey methods changed substantially over time?	4	1	1	1	1	1	0	12
Are data shared publicly e.g. NBN?	2	3	2	2	2	2	0	12
Motivations for biodiversity monitoring?								
Examine effectiveness of individual restoration methods	8	2	2	1	5	2	1	12
Examine success of project as a whole	9	3	1	1	4	2	1	12
Because it's a requirement of funding source	2	0	0	0	0	1	0	12
Which funders stipulate biodiversity monitoring?								2
EU LIFE	1							
AWPR mitigation	1					1		
Are data sufficiently robust to test biodiversity responses?	7	2	0	0	4	1	1	12
Are data available for meta-analyses?	7	4	3	2	6	3	1	12
Are monitoring reports available?	7	4	2	2	6	3	1	12

Table 1b continued

	Vegetation	Inverts	Reptiles	Amphibians	Birds	Mammals	Micro-orgs	Responses
Evidence of success in terms of biodiversity responses?								5
Too early	1							
Published papers	1							
Unpublished reports	1	1			1	1	1	
Unspecified source					1			
Do you have limitations to doing more monitoring?								2
Yes (unspecified)	1	1			1	1		
Funding	1	1	1	1	1	1	1	

Table 2. Deployment of different study designs at peatland restoration projects. Table shows number of sites per taxa/study design combination. Note the first three are considered formal study designs that have the potential to yield robust, analysable data. The remainder are described here based on reported monitoring

	Before-After-Control-Impact (BACI)	Control-Impact (CI)	Before-After (BA)	Before-Control (BC)	After (A)	Before (B)	Control (C)
Vegetation	4	2*	2	1	1	1	
Invertebrates		1	2*		3	1	1
Microbes					1		1
Reptiles			2*		1		1
Amphibians			1*		1		1
Birds		1	3*		1	1	1
Mammals		1	1*		1		1

*denotes casual (ad-hoc) monitoring only at one of these sites

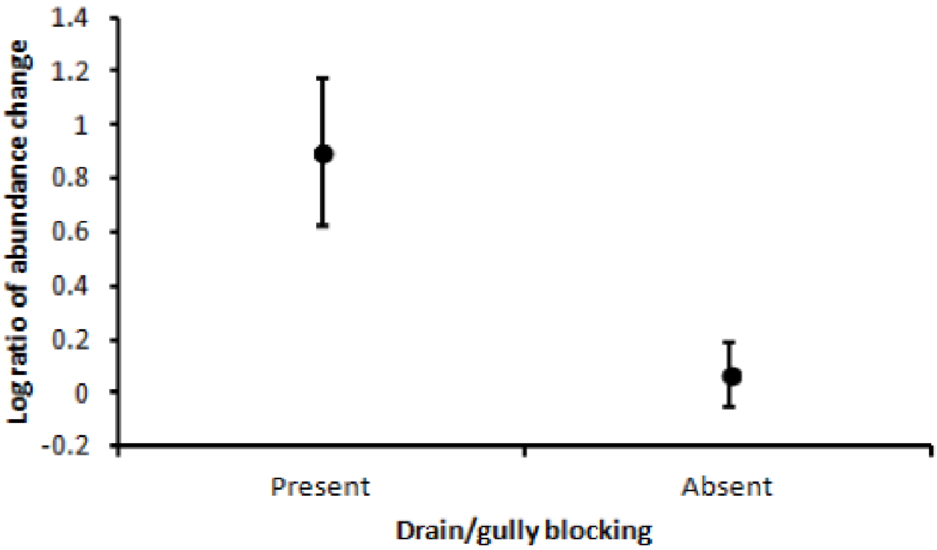
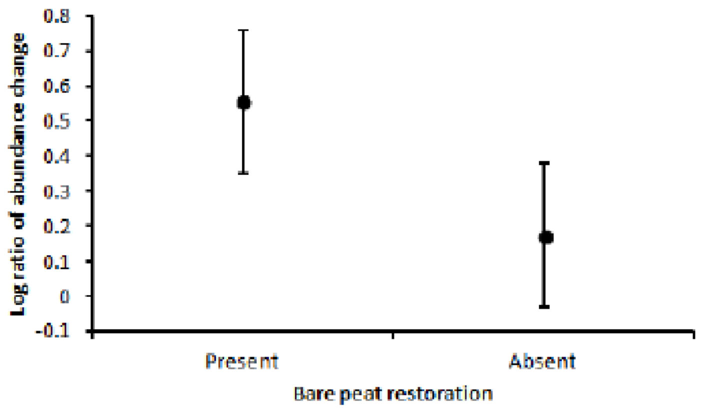


Fig. 1. Relationship between change in abundance of Golden Plover between surveys (on the y-axis; 0 = no change; 0.5 = 65% increase; 1 = 172% increase) and the presence/absence of drain or gully blocking management. Plot shows the predicted mean values (± 1 SE). model.



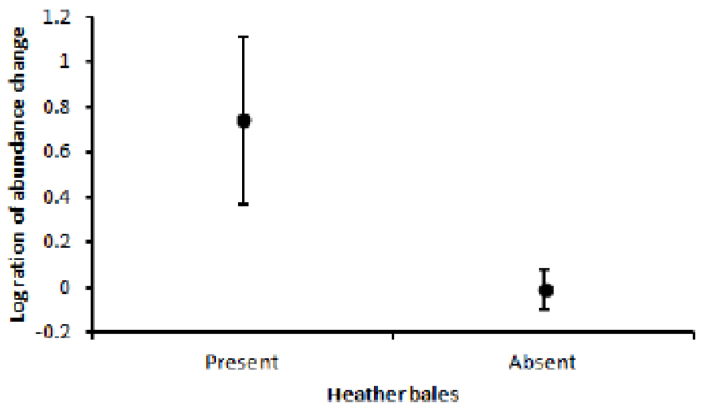


Fig. 2. Relationships between change in curlew abundance between surveys (y-axis; -0.5 = 40% decline; 0 = no change; 0.5 = 65% increase; 1 = 172% increase) and presence/absence of (a) bare peat restoration, and (b) heather bales for blocking drains. Plots show the predicted mean values (± 1 standard error) from multivariate model accounting for the mean values of the other terms in the model.

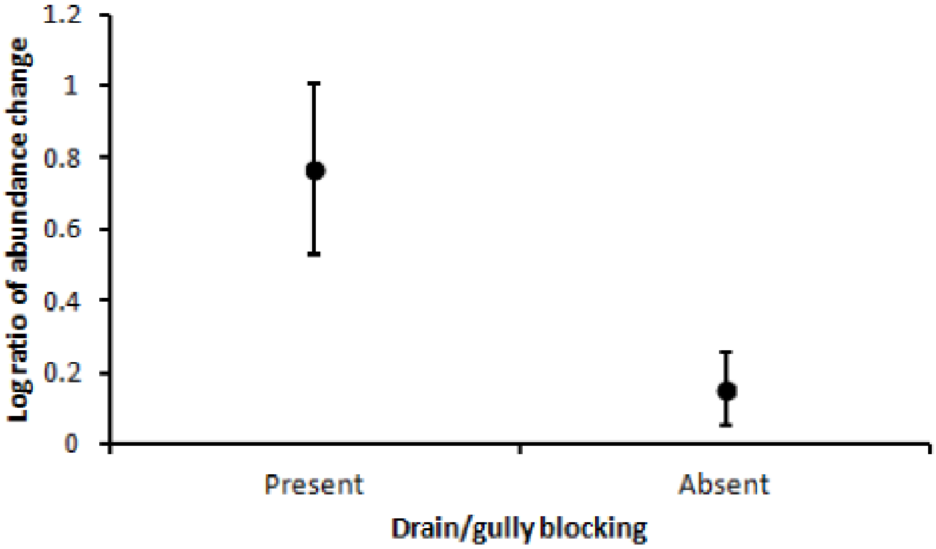


Fig. 3. Relationship between change in skylark abundance between surveys (y-axis; 0 = no change; 0.5 = 65% increase; 1 = 172% increase) and the presence/absence of drain/gully blocking management. The plot shows the predicted mean values (± 1 standard error) from the model.

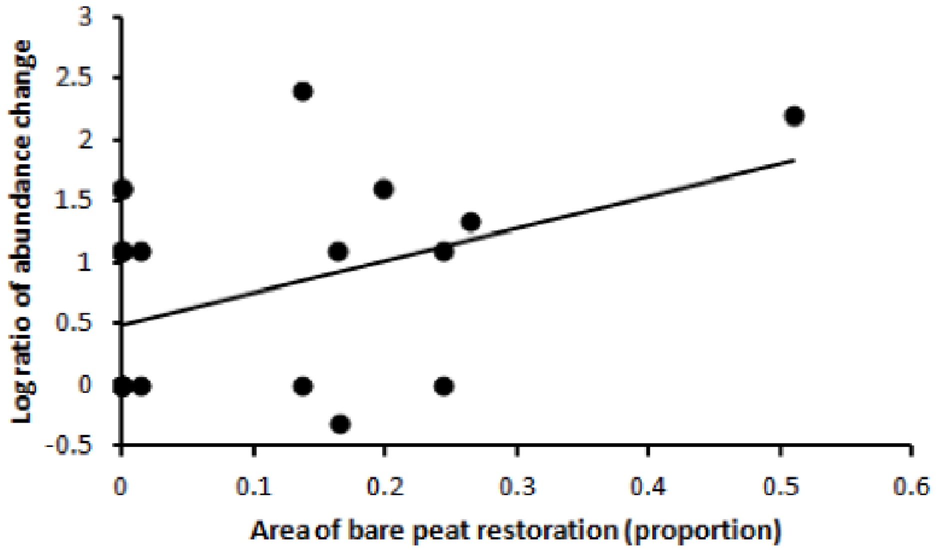


Fig. 4. Relationship between change in dunlin abundance between surveys (y-axis; -0.5 = 40% decline; 0 = no change; 0.5 = 65% increase; 1 = 172% increase) and area of bare peat restoration as a proportion of the 1-km square. Plot shows the observed data (circles) and predicted relationship (line) from a multivariate model accounting for the mean values of the other terms in the model.

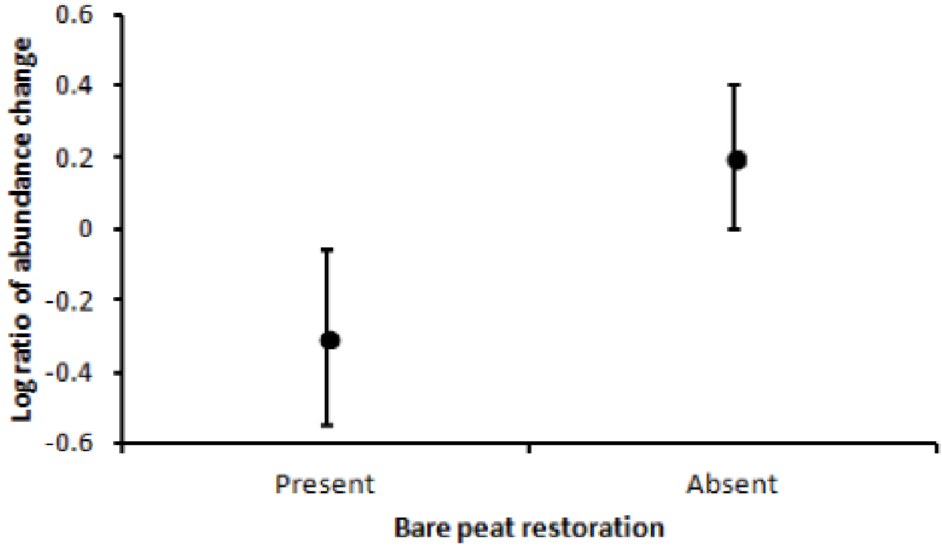


Fig. 5. Relationship between change in meadow pipit abundance between surveys (y-axis; -0.5 = 40% decline; 0 = no change; 0.5 = 65% increase) and presence/absence of bare peat restoration. Plot shows the predicted mean values (± 1 SE), accounting for the mean values of the other terms in the model.

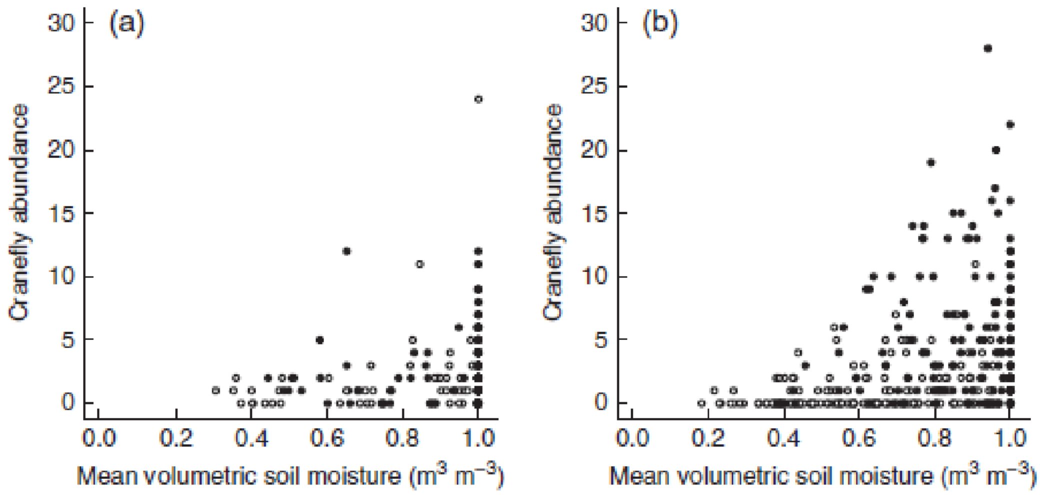


Fig. 6. Relationship between mean volumetric soil moisture and cranefly abundance, for sampling locations at blocked drains (filled circles) and unblocked drains (open circles), in (a) 2009 and (b) 2010. From Carroll et al (2011).

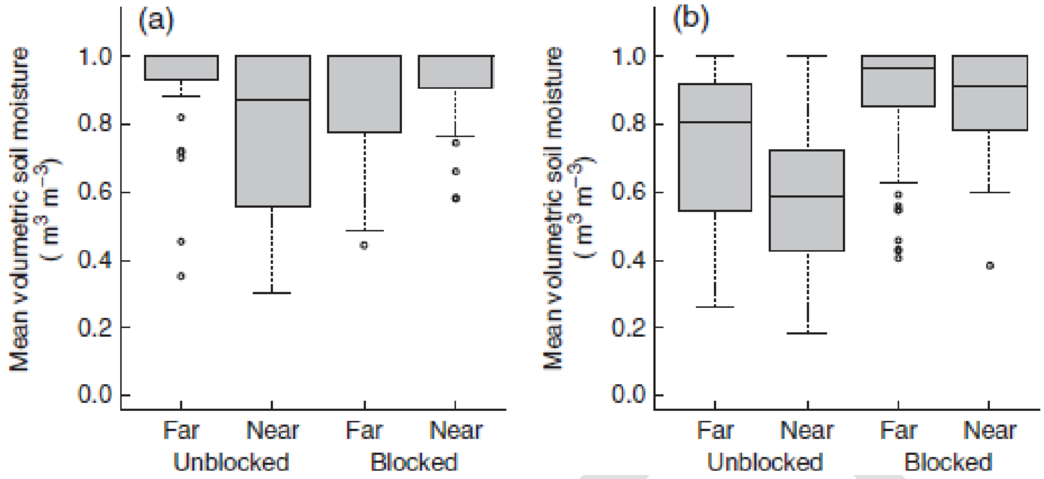


Fig. 7. Comparison of mean volumetric soil moisture, between blocked and unblocked drains, and at the drain edge (Near) and 10m from the drain (Far), for (a) 2009 and (b) 2010. Box midline indicates median, box edges indicate interquartile range. Whiskers indicate range of data; points indicate data outside 1.5 x the interquartile range. From Carroll et al (2011).

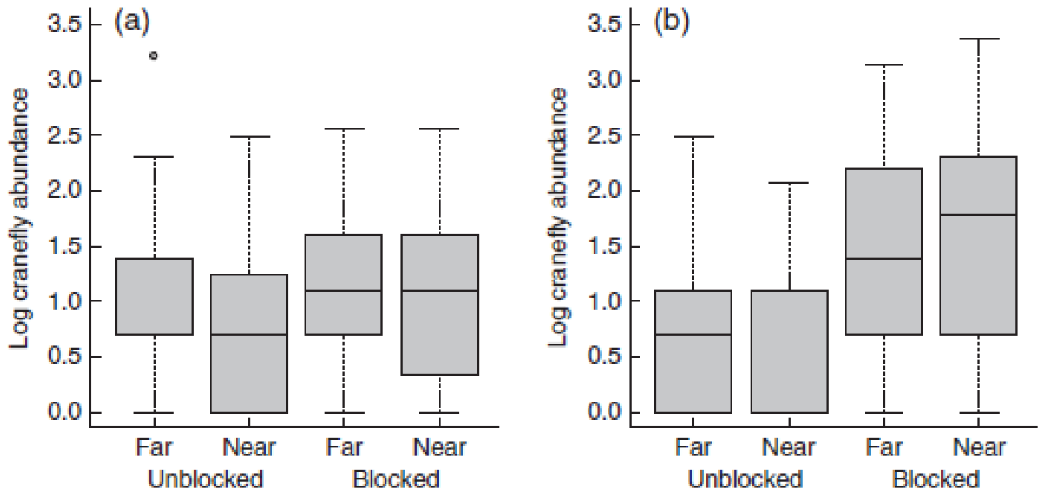


Fig. 8. Comparison of log cranefly abundance between blocked and unblocked drains, and at traps at the drain edge (Near) and 10m from the drain (Far), for (a) 2009 and (b) 2010. Data were transformed as log(1 + abundance) before plotting. Box midline indicates median, box edges indicate interquartile range. Whiskers indicate range of data within 1.5 x the interquartile range; points indicate data outside 1.5 x the interquartile range. From Carroll et al (2011).

Appendix 1. Summary of existing monitoring guidance

Here we summarise (a) existing guidance for monitoring at peatland restoration sites from Natural England, and consider two additional frameworks for potentially assessing responses to restoration: (b) Common Standards Monitoring; (c) The trajectories approach.

(a) Existing monitoring guidance from Natural England

This draws on two Natural England technical reports (Bonnett et al 2009; Natural England 2011) that recommend that monitoring should follow these principles:

(i) Setting objectives for restoration

The restoration goals and objectives of the project need to be agreed and defined before the monitoring techniques are selected and before any restoration work starts. The range of potential causes and mechanisms of degradation should be identified, and potential future degradation addressed. The objectives should then describe the desired end-point for the peatland in terms of habitats, functions or uses, with reference to a suitable control site/s. A control site need not be 'pristine' but could simply be a site that is considered to be 'much better' in terms of its condition. If the region holds few undamaged peatlands, then the reference site might even be an old restoration site that is well advanced towards recovery. The monitoring techniques selected should reflect the objectives, budget and scale of the restoration project. The data produced by the monitoring should be capable of:

- Describing the extent to which the restoration objectives have been met;
- Indicating the extent to which changes are due to restoration or wider environmental factors;
- Showing whether recovery processes are sufficient to overwhelm any remaining degrading processes (e.g. climate change, diffuse atmospheric pollution; high deer numbers)

(ii) Establishing a monitoring programme

Once restoration objectives have been set, and monitoring techniques selected, the programme should identify monitoring targets. These are the target values that the monitoring data should attain, for example with reference to control sites, that will indicate when the restoration objectives have been met. There should be clear and measurable criteria by which to judge restoration success. The statistical methods that will be used to analyse the data will influence data collection. Projects should also consider how the monitoring results will be communicated, their potential audience and their likely reaction. This may influence the parameters monitored and techniques used.
Ideally monitoring should start before restoration takes place and cover both pre-restoration and post-restoration phases. This means that establishing a monitoring programme should be among the earliest steps in a peatland restoration programme. If adequate pre-restoration monitoring is not possible, past survey or environmental data may help, but you should consider how to make the new monitoring programme compatible

with the techniques and methodologies used in past surveys. An important factor here is the degree of replication. If there is no replication, then 'before' data is essential. Otherwise, attribution of outcomes to restoration management (rather than pre-existing differences) becomes impossible. But if you have several replicates in both the restoration and control categories, and these groups of sites are comparable in factors such as topography, peat depth and management history, then attribution is more likely to be reliable.
If possible, sufficient resources should be sought for the whole of the proposed monitoring programme. Projects should also ensure that access to sites will remain possible throughout the programme, for example through agreements that can survive changes in ownership. Measurements should be made at a sampling density necessary to account for natural variability in site conditions, and to provide sufficient sample size to enable statistical tests to detect the changes you wish to report (to detect smaller changes in more variable parameters will require more samples). In reality, the number and frequency of measurements is likely to be a compromise between keeping costs down and producing the best scientific information. Consideration should be given at the start of the programme to the use and dissemination of the monitoring data, and where possible, it should be collected in a form that is compatible, accessible, easily shared with others and not subject to restrictions due to intellectual property issues.

(iii) Selecting monitoring techniques

See specific guidance in Natural England (2011) and Bonnett et al (2009).

(iv) Identify the required resources and timescales

Monitoring should be conducted over a sufficient timescale to enable detection of agreed recovery outcomes. Monitoring should cover a sufficient duration and frequency to allow for inter-annual and seasonal effects which might obscure the impact being assessed.

(v) Analysis and assessment

To evaluate whether the restoration objectives have been met, the monitoring data must be interpreted against criteria. These criteria may be based on:

- Direct comparison with a 'reference' site which already meets your objectives
- Comparison with accepted threshold values (for example, from JNCC Common Standards Monitoring)
- The overall direction of change (trajectory analysis) compared to initial conditions or unrestored areas

Statistical techniques will be required to test whether any changes observed in the monitoring programme are statistically significant. It is also important to separate out clear hypotheses (e.g. 'mean water table will rise [by target amount] after 1 year'; '*Sphagnum* cover will increase [by target amount] after 5 years') from descriptive statistics (describing the changes vegetation community over time and interpreting with relation to ecology of the various species). It is necessary to decide which techniques to use early during design and conception stages of the monitoring protocols. This is because statistical tests often require certain types of data to be collected to be valid. Interpretation of monitoring data will be enhanced by available information on environmental trends in the surrounding area. This might include weather station data, biological records or atmospheric pollution data.

The restoration management put in place may not succeed in delivering the project's objectives. Therefore, even with the best-designed monitoring scheme, the data collected may not be capable of capturing unpredictable changes, or helping explain changes, owing to the complexity of ecosystem interactions. Assessment of monitoring information during the course of the project can indicate where restoration management is failing to deliver objectives, and enable new restoration approaches and treatments to be applied ("adaptive management"). Ideally, any such follow-on managements should be set up experimentally, so that their impact can be measured, in comparison to other areas that are left without additional management. Where this happens, it may be necessary to review the monitoring programme to ensure that the monitoring techniques are still appropriate. If monitoring information indicates that restoration objectives are not likely to be met, this information can be used to help set new restoration objectives themselves.

(vi) Data sharing

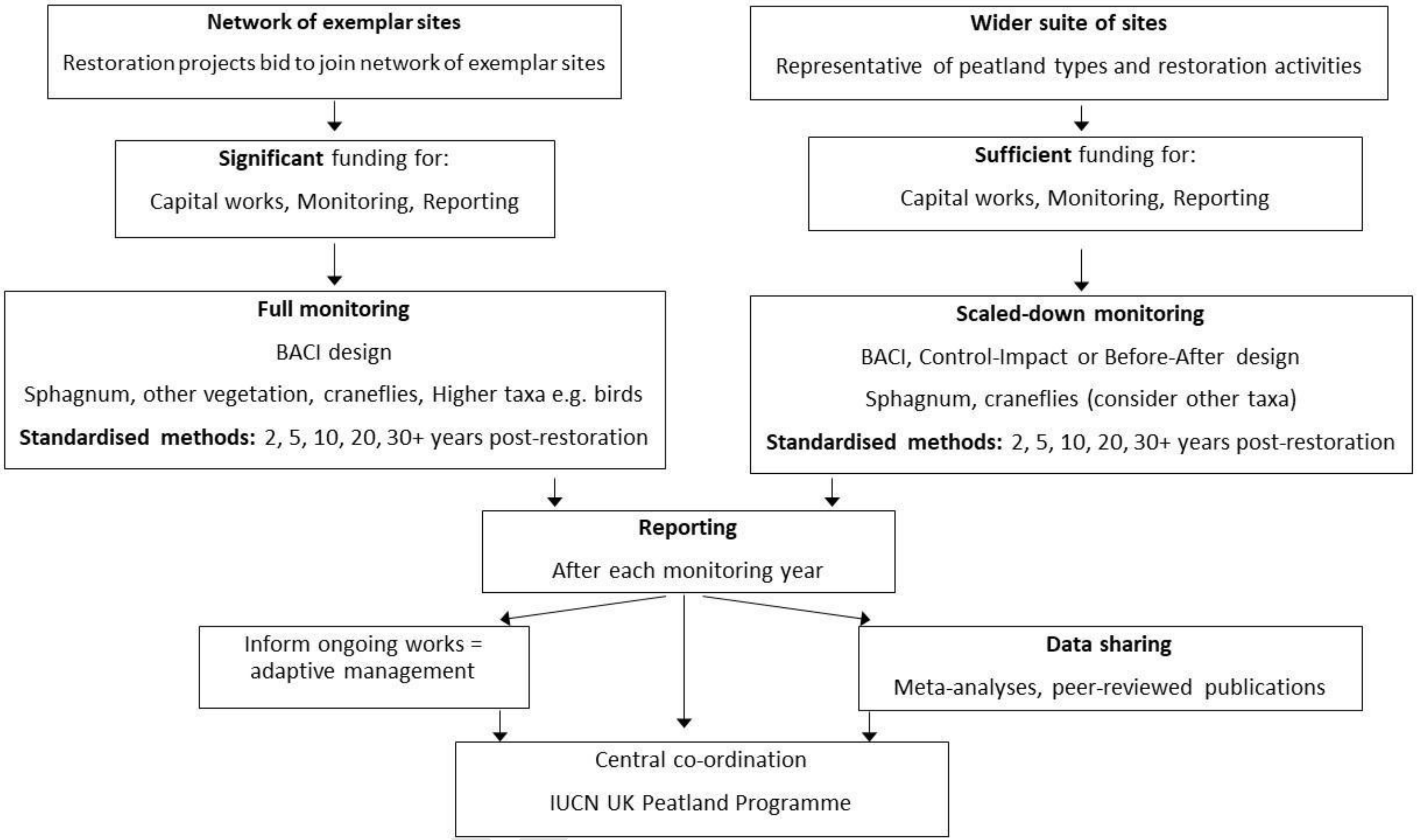
While analysis of monitoring data can inform the management of a single restoration project, analysis of data from across restoration projects, either a range of different peatland types employing different restoration techniques, or replicates of similar restoration projects, can provide a wider overview of peatland responses, which can be used to inform methods, guidance, policy and future research. Monitoring information can contribute to established networks designed to assess long-term or widespread environmental impacts.

(b) Common Standards Monitoring

Common Standards Monitoring (CSM) is a monitoring framework developed by the statutory conservation agencies in the UK for reporting on the condition of habitat and species features in designated nature conservation sites under UK and EU legislation (JNCC, 1998). Peatland habitats are covered in the CSM guidance for lowland wetland (JNCC, 2004) and uplands (JNCC, 2009) which mainly use set vegetation composition (including positive and negative indicators) and structure 'attribute' targets to assess current condition. However, CSM is not designed to evaluate the effect of particular interventions such as peatland restoration and might not therefore provide the most appropriate framework for monitoring biodiversity responses.

(c) The trajectories approach

The trajectories approach has been developed in collaboration between Natural England's Major Landowners Group and the RSPB. It is intended to address a shortcoming in CSM for site monitoring, by identifying and monitoring key selected variables and milestones with the aim of identifying improvement short of achieving favourable condition. It has been applied to monitor the recovery of SSSIs following restoration management and uses key 'indicator' species or groups, e.g. cover of *Sphagnum* mosses, and other variables to track recovery through progress in meeting pre-determined targets or 'milestones' at set time intervals along a 'trajectory' towards 'favourable condition'. Such variables could include proxy measures of peatland function such as water table or quality. The trajectories approach was demonstrated using data from a Dark Peak blanket bog restoration site, Dove Stone (Groom 2015). Further work done in collaboration with NE to support the use of the approach for blanket bog restoration monitoring has included a review of timescales for recovery following different restoration interventions (Penny Anderson Associates 2014). Collation and analysis of restoration monitoring data by Moors For The Future Partnership (MFFP) has also been undertaken on their own restoration sites in the Peak District and from bog restoration work done by the Yorkshire and North Pennines peatland restoration partnerships. The latter shows that measures such as bare peat cover, cover of key plant species, including *Sphagnum*, and diversity measures of appropriate species such as species dominance and richness, show fairly predictable changes over time (Pilkington et al 2016). Another aim is to provide a simple, flexible method that can be used by those with differing skill levels and resources. However, it has not yet been fully developed or adopted for blanket bog monitoring, though the general approach underpins the Blanket Bog Restoration Strategy for England (Defra 2015) and in simple form is being recommended by NE for monitoring the effect of restoration interventions under upland Long-Term Plans in England (D Glaves in litt.). The trajectories approach in current format is therefore unlikely to provide the most appropriate framework for monitoring biodiversity responses.



Appendix 2. Schematic of future approach for standardised biodiversity monitoring at UK peatland restoration project