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Peatland restoration – a comparative analysis of the costs and merits of different restoration methods

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1. Executive Summary

Peatlands cover nearly a quarter of Scotland and contain over half of the total Scottish soil carbon. However, more than 90% of the lowland raised bogs (and over half of the blanket bog) have been altered to such an extent that they are now degraded, causing substantial Greenhouse Gas (GHG) emissions and release of dissolved and particulate carbon into waterways. Scottish Government has set ambitious peatland restoration and rewetting targets in the Climate Change Plan and a large funding programme in the shape of Peatland Action has been in place since 2012. This project examined the costs and benefits of peatland restoration activities in Scotland to get a sense of the cost effectiveness of different techniques, primarily targeting work carried out since 2010.

2. Key findings

- Rewetting techniques for drained blanket bogs and raised bogs are generally very similar techniques. Evidence to date suggests that peat dams remain intact for up to six years after installation, but a small proportion show evidence of erosion. Deeply cracked peat can be problematic but some results suggest that repacked trench techniques and related membrane-based techniques may be successful in raising the water table. Results of restoration on formerly afforested areas depends on the age of trees to be felled, and only the combination of felling and drain/furrow blocking results in the consistent recovery of the water table over time.
- Restoration of extensive areas of bare peat is challenging and evidence suggests that techniques must be applied to local circumstances, perhaps combining the use of geotextiles and some form of re-seeding, sometimes blocking gullies with rocks and other material to slow the flow of water.
- We found a large number of reports detailing substantial ecosystem benefits of peatland restoration practices; however the literature to date suggests that these only rarely approach the level of a near natural site. This may be due to the relatively early nature of many of these projects.

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- Average costs per unit restored, for the 26 restoration interventions with data of sufficient reliability, were generally similar between different intervention options. The exception was erosion control, where intervention cost varied between hundreds and tens of thousands of pounds per hectare. Better reporting processes for costs have now been established that should mean that future cost-effectiveness evaluation is more straightforward.
- Effectiveness of the techniques, both immediately after completion and within the year after completion, was deemed very high, although some techniques, such as forestry and scrub control, are likely to require higher levels of maintenance in the longer term. Due to the lack of any common monitoring protocol across peatland restoration sites in the UK, we relied on perceived effectiveness, rather than a standardised measure of observed effectiveness. Future peatland restoration projects should consider adopting a common protocol for recording changes in ecosystem service delivery, to enable a more robust evaluation of the cost-effectiveness of such projects.
- The area restored by various interventions can be difficult to define. We recommend the development of guidance to ensure a standard method is used to estimate the area affected by the restoration intervention.

3. Conclusion

Despite the constraints in availability of data, we found policy-relevant information to shed light on which techniques work in certain circumstances to achieve the initial goal of sustainable rewetting of peatlands. This can help to inform further restoration work going forward, although longer term data monitoring protocols should be prioritized to support more in-depth cost benefit analysis over the full life-time of rewetting to stable condition.

Contents

4. Introduction

The majority of Scotland's nearly 2 million hectares of peatland have suffered from some form of damage. It is estimated that over 90% of the lowland raised bog and fen habitat and more than half of the blanket bog has been altered (Artz et al., 2013). These areas are generally no longer peat forming and instead are actively emitting carbon in various forms, thus contributing to the net GHG emissions for Scotland (Chapman et al., 2012; Artz et al., 2012). Restoration activities halt further habitat decline, safeguard the remaining soil carbon stock and decrease total GHG emissions (Evans et al., 2017). The number of peatland restoration projects has increased across Scotland since the early 1990's, with the majority of the restoration efforts having taken place since 2010, largely due to the start of major public peatland restoration funding availability (Chapman et al, 2012).

While there is mounting evidence that peatland restoration can contribute to achieving national emissions reduction targets (IPCC 2014), restoring peatland habitat is also considered of internationally high importance to achieve Aichi target 15 given that the UK land mass contains an estimated 10-15% of the global blanket peat. Aichi target 15 aims to enhance ecosystem resilience and the contribution of biodiversity to carbon stocks, through conservation and restoration, including restoration of at least 15% of degraded ecosystems (https://www.cbd.int/aichi-targets/target/15). This has led to the inclusion of peatland restoration as a policy instrument into the Climate Change Plan. Peatland restoration approaches will vary, depending on the factors that contributed to their degradation. For example, some sites were drained for timber production, or to improve the grazing quality of the uplands, and as a result 28% of the Scottish peatlands are estimated to show signs of drainage (Artz et al., 2017; Aitkenhead et al., 2016). Drained sites in the lowland can additionally be prone to scrub invasion. Other activities, such as historic deforestation and subsequent erosion of exposed peat, in some cases combined with high grazing and trampling pressure, have led to large areas of exposed peat. These areas are prone to further degradation as the lack of a surface vegetation layer means that climatic influences (rain, wind, frost) can accelerate the process. There have been a number of studies that demonstrated the losses of carbon from such impacted sites and we refer the reader to a number of existing reviews and project reports for further details (Lindsay, 2010; Couwenberg et al., 2011; Artz et al., 2013; Smyth et al., 2015; Wilson et al., 2015; Evans et al., 2016). The impact of peatland degradation on habitat quality, bird species of international concern and carbon emissions, was beginning to be realized by the early 1990s and started the beginning of peatland restoration efforts.

Peatland restoration activities therefore differ depending on the starting conditions on the site, and in some cases, a complex mixture of interventions are required. We investigated five primary rewetting activities (Table 1). Techniques for restoring sites that have been afforested will depend on the age of the timber crop, the nature of drainage and other planting practice, and whether there are nearby sites that could act as (direct or indirect) donor sites for the peatland species that are to re-establish. Rewetting on formerly afforested sites may range from simply blocking up collector drains to blocking the individual plough furrows created at planting. In many cases, a further round of management was deemed necessary on fell-to-waste sites which included crushing of the remaining brash, flipping the tree stumps upside-down and/or ground smoothing to eliminate the relict ploughing pattern. Scrub removal techniques range from herbicide spraying to removal via mechanical means, with the material generally left on site.

Table 1. Rewetting activity categories investigated

Primary rewetting activity	*Individual activities within primary category*
Erosion or other bare peat control	reprofiling, re-seeding, geojute application, native bog woodland recreation, channel damming
Ditch blocking	peat dams, plastic/heather/wood dams, trenching, bunding, cell bunding, reprofiling, channel damming
Domestic cuttings reprofiling	Reprofiling
Plantation forestry removal	felling, whole tree harvesting, whole tree mulching, furrow-blocking and brash crushing, stump flipping/ground smoothing
Regeneration or scrub control	spraying, weed-wiping, hand pulling, cutting with brush/clearing saw, cutting with chainsaw, manual felling

Drain blocking can include blocking by hand, with peat, timber, rock, heather bales or plastic dams at regular intervals, as well as mechanical means of blocking drains by using a low ground pressure digger to move sections of peat into the path of the drain. More advanced methods of these include drain (or grip) reprofiling, a technique where the ground beside the drains is squashed down so that the sides of the drains get pushed in and more or less meet in the middle, closing the channel . Drain reprofiling, contrary to standard drain-blocking does not involve digging up a large section of peat and therefor does not create a new water body. However, the Snowden and Sharman Yorkshire Peat Partnership report (Green et al., 2011) states that the practice of reprofiling grips was discontinued because there was evidence that it led to increased methane emissions. On eroded or other bare peat sites (such as peat cuttings), there are similarly a large number of possible interventions, but in all cases, the intention is to decrease the overall area of bare peat. Therefore, the interventions range from blocking up eroding gullies with dams (often stone) to establishing vegetation via mulching with heather and seed containing mixes, direct seeding or transplantation of peatland species, to covering the areas with geotextiles.

The overall aim of this project was to examine the costs and merits of the different practical techniques deployed to deliver peatland restoration projects in Scotland since 2010. Previous reviews either focused primarily on costs of the interventions (e.g. Chapman et al., 2012, Artz and McBride, 2017) or collated observed ecosystem service benefits or efficiencies of the interventions in a qualitative way, thus precluding formal cost-benefit or cost-efficiency analyses (e.g. Artz and McBride, 2017). Glenk et al. (2014) presented a framework for economic (cost-benefit) evaluation of peatland restoration, but did not include any reference to cases studies within the UK. Andersen et al. (2017) reviewed the outcomes of EU-LIFE restoration projects between 1993 and 2015, which covered 80 projects across Europe, including some in the UK. They concluded that, while positive progress due to restoration activities could often be described for individual sites, comparative analyses were difficult due to a lack of a common set of scoring criteria to determine whether the target had been reached. In addition, many projects did not seem to state unambiguous targets for the project, and/or lacked monitoring, unrestored control sites or nearby locations that were in a reference state. Glenk and Martin-Ortega (2018) presented a case study of peatland restoration based on stated preference surveys and average costs of peatland restoration and found that, at this general level, peatland restoration was producing overall welfare enhancing results in Scotland. Our approach is detailed in Appendix 1.

5. Results

Review of peatland restoration techniques and their effectiveness

A total of 70 publications, of which 59 were published papers or reports and 11 PhD theses, were included in our literature review (see Appendix 4 for details).

Techniques for restoring drained peatlands and their immediate effectiveness

Drained blanket bogs and raised bogs generally share very similar techniques for rewetting, with the main differences primarily in the restoration of perimeter drains and differences in tackling blocking drains on steeper slopes. A break in the downstream line of the drain is created by means of insertion of dams made of plastic piling, wood, stone, hay or heather bales, or, most frequently in recent years, by moving a block of adjacent peat into the drain with the aid of a digger. All of these techniques slow down the flow along the drain, and therefore tend to create small pools immediately upstream of the dams (Parry et al., 2014; Armstrong et al., 2009). Experimental techniques try to avoid moving blocks of peat and creating water bodies by 'pinching' the sides of the drains, which moves some peat into the drain itself (A. McBride, pers. Comm.). Snowden and Sharman (2017) assessed the effectiveness of Yorkshire Peat Partnership's peat dams, grip reprofiling, reprofiling bare peat in hag and gulley erosion situations and revegetating bare peat in the same situations. Peat dams in grips were examined 1-6 years after installation and 94% were found to be intact, with 12% showing signs of erosion. On average the 5 m of grip directly upstream of the dam had 72% (by area) revegetated with the main increasing species being Hare's-tail cottongrass and some *Sphagnum* species. Grips that had been reprofiled to reduce the steepness of the sides and width of the channel, a technique now discontinued in Yorkshire due to concerns over potential methane emission increases, had better revegetation and a lower incidence of erosion than those that had not.

Drain blocking can be highly effective for improving both carbon storage potential and upland water quality (Wallage, 2007). At Oughtershaw Beck in the Yorkshire Dales, drain blocking caused an average 4 cm rise in the water table, increasing surface saturation and overland flow frequencies and reducing microbial activity and

DOC production rates by 50%. Some evidence that raising water tables may promote vegetation change in *Molinia*-dominated blanket bogs was reported by Gatis (2015), who also noted the failure of drain blocking to always significantly change water levels and CO_2 fluxes in the short term. This research left the question open as to whether drain blocking can raise the water table sufficiently to protect the peat store, change the vegetation and reinstate carbon sequestration. Restoration action may not, in the short term (15 years) restore net carbon sequestration on severely damaged lowland raised bogs. Dooling (2014) reported that older restoration areas on Thorne and Hatfield Moors had higher methane emissions than younger restoration areas. The restoration areas all had a net global warming potential (i.e. net climate warming effect of CO_2 and CH_4 emissions) and for the older restoration areas it was significantly greater than that of unrestored areas of the sites. There is as yet no evidence on whether these effects are transient or indicative of unsuccessful restoration.

Techniques for restoring afforested peatlands

All felling techniques achieve the immediate desired result of removing the standing tree biomass, but there are differences in the desired immediate effects between different management practices. Some aim to achieve a surface as closely resembling a flat surface as possible, whilst others aim to reduce the amount of conifer biomass, or a combination of these. Anderson and Peace (2017) showed evidence from 3 sites in the north of Scotland where various restoration practices had been tested over a 10 year period on experimental plots. Their findings were that the felling was required to increase the water table in restoration sites; leaving the trees whilst rewetting was insufficient to create a water table high enough to kill the trees over time. Similarly, restoration treatments that felled the trees without damming the drains and plough furrows were insufficient to raise the water table consistently. Only the combination treatment of felling (either with or without tree removal or debranching) and drain/furrow blocking resulted in consistent recovery of the water table over time. The vegetation composition of felled treatments had reverted partially towards that of the open bog control, but was still significantly different from the intended target in all different treatments tested. Increased overall peat depth, measured by a fixed rod fixed permanently to the clay beneath the peat layer was, observed as was a decrease in bulk density. This suggests some level of decompression of the peat after the subsidence events caused by afforestation. There was also an observed relationship between the density of conifer seedlings through regeneration and the distance to the remaining standing crop.

Hancock et al., (2018) showed similar mixed success of restoration by felling to waste on the vegetation structure over a 13 year period, noting a poorer response on former plough ridges and also a negative effect on the recovery of typical bog forming vegetation on steeper slopes across the site. Water chemistry effects in the first year after restoration were reported by Gaffney (2016). Phosphate, potassium, ammonium and dissolved organic carbon (DOC) increased in soil pore water and surface water but only phosphate and iron increases were found in streams. No significant effect on organic carbon export was seen. While a chronosequence of restoration sites showed progressive recovery towards bog conditions, incomplete water table recovery and elevated pore-water ammonium were seen as barriers to restoration success, leading to the recommendation that enhancements such as brash and needle removal and plough furrow blocking be tested (Gaffney, 2016). Rankin (year unknown) summarized progress with a trial of ground smoothing and cross-tracking techniques for dealing with the relict forestry ploughing pattern on afforested blanket bog undergoing restoration following tree harvesting. The ploughing was antagonistic to restoration because the ridges remain high and dry after drain blocking and thus support atypical bog plants and naturally regenerating conifers. Ground smoothing by flipping the stumps over into the furrows, thus blocking them, was successful in retaining water on site, and there were signs that it made it wetter, killed the regenerating conifers and reduced heather cover. Cross-tracking the ploughing with an excavator (a less intensive option suitable for areas with partially rotten stumps) tended to produce similar results but to a lesser extent. The techniques were suitable for large-scale application. Ground smoothing cost £850 per ha (2016a, IUCN, 2017). A new technique, wave damming, was also developed as a cost-effective method of damming forestry drains with peat. The durability of the dams has not yet been reported but taking less than a minute per dam, it has the potential to be extremely cost-effective, costing £350 per km of drain for dams at 4 m intervals (IUCN, 2016a, 2016b, 2016c, 2017). It has also been used to dam deep double-mouldboard plough furrows.

Techniques for semi-natural woodland, conifer regeneration and scrub encroachment

Unrestored, but also previously restored, peatlands can be encroached by woody species, inclusive of commercial forestry conifers, if the environmental conditions have not been sufficiently restored to compete such species out, i.e. the site is not sufficiently rewetted. Such ‘scrub’ can include semi-natural woodland species such as birch, willow and Scots pine; however the definition excludes bog woodland, which support peatland hydrology as well as woodland/peatland flora. In addition, there is often establishment of species such as gorse or rhododendron on the drier edges of sites. Techniques for removal include hand pulling small and sparse individual seedlings. These should be laid on the ground with the roots facing upwards so that they dry out and cannot re-root. Denser scrub can be removed using brush cutters (<5 cm stem diameter or multiple stems) or chainsaws. Scrub should be cut below the lowest set of branches to avoid re-growth and all stumps (except conifers) should be treated with 10% glyphosate mixed with a colouring agent to check coverage is complete so that re-growth cannot occur. Glyphosate treatment can also be directly applied to standing vegetation, avoiding water courses, and generally has to be repeated a few times to ensure that the scrub does not recover. As already recognized in the IUCN Peatland Hydrology review (2010a), little seems to have been published on the effects of scrub encroachment or indeed scrub removal on peatland functioning. We were able to find very few UK examples of the effectiveness of scrub removal. For example, the scrub removal work at Portmoak Moss was repeated several times since 2010, and although the core of the site has been reported as much improved in wetness, it is surrounded by mature trees and hence the current Portmoak

Moss Management Plan recognises that encroachment by scrub will be a continuing challenge (Woodland Trust Scotland, 2017). The IUCN Impacts of Peatland Restoration review (2010b) reports empirical evidence of generally immediate positive effects on the stability and height of the water table due to reduced uptake of water by scrub and reduced evapotranspiration as well as effects on carbon sequestration and biodiversity; however the data sources were not specified. Outside of the UK literature, however, Klimkowska et al (2010) found that a combination of herbicide and annual mowing was the most effective in limiting willow shrub regrowth on fen meadows, or several mowing interventions in the first few years if herbicide was avoided. Kotowski et al (2013) showed that scrub removal did lead to enhanced establishment of target vegetation in a drained and subsequently rewetted fen, although the authors recommended using this intervention only where some of the intended vegetation still remained. The authors of the IUCN Peatland Biodiversity (2010c) report, however, also mentioned that some native scrub on bogs may be valuable as habitat for rare invertebrate species.

Techniques for rewetting cracked peat

In the final report of the 2014-15 Peatland Action project ‘Longbridge Muir Restoration Project’, Anderson and Graham (2015) reported on a trial of rewetting of deeply cracked peat, which had failed to rewet after damming drains and plough furrows ten years earlier on this lowland raised bog. The repacked trench technique used in ‘cell bunding’ and a related membrane trench technique were tested in a replicated field trial. Both techniques were successful in raising the water table to a level conducive to bog recovery. The repacked trench technique, used here in a contour aligned configuration, not as a series of cells, was much cheaper to implement and therefore recommended as a cost-effective treatment for rewetting other sites with deeply cracked peat. The full results of this trial and a similar trial of these techniques used for rewetting cracked blanket bog peat are soon to be submitted for peer-reviewed journal publication (Anderson and Saunders, in prep 2018). This paper will report similar success of the techniques on blanket bog, although furrow damming, which was also trialled, was almost as successful on the less deeply cracked blanket peat. The costs of implementing the repacked trench and furrow damming techniques in this context need to be assessed to compare their cost-effectiveness. Another technique used for cracked peat (but also other peat damage types) is bunding, the installation of a wall of compacted peat, which acts as a barrier to surface and sub-surface water leaving the site. This technique can be very effective at retaining water and allow deeply cracked peat to fill in with surrounding peat. However, the technique can also lead to (temporary) flooding within the bunds if they are very effective, as was observed at e.g. Glasson Moss SSSI (South Solway Mosses, North Cumbria), or can fail if there is unexpected subsurface flow below the bunds (peat pipes or extant ditches).

Techniques for restoring bare peat

Eroding peatlands often exhibit extensive areas of *entirely* bare peat, often in deeply incised gullies, and therefore the most immediate concern is stopping any further loss of peat. Techniques have varied in restoration projects to date and are often unique to the situation at each site. In the largest eroded areas, geotextiles and some form of re-seeding have often been used, in some case this involved fast growing grasses combined with fertilizer application (e.g. Stimson et al., 2017; YPP (year not available); Anderson et al., 2009). This did not lead to short-term increases in fluvial carbon exports as had been feared (Stimson, 2016). In a Scottish context, a more commonly used approach is blocking of the gullies, often with rock, combined with application of heather and moss mixtures from a nearby donor site. The purpose of gully blocking is not to complete block the pathway of water, but instead to slow down the flow and therefore create areas of low flow where particulates can settle out, thereby gradually increasing the peat depth in such areas (e.g. Martin-Ortega et al., 2014).

Snowden and Sharman (2017) found that there was less evidence of successful restoration on bare peat slopes on hags and gully sides. Reprofiling and revegetating the slopes resulted in 55% revegetation and revegetating alone gave 47% revegetation. Revegetation by turf placement had sometimes failed due to slippage and rooting failure and ongoing erosion of the slopes was common. Newer revegetation techniques thought likely to improve success were not assessed. Large areas of bare and eroding blanket bog with *Sphagnum* mosses scarce or absent from the vicinity could benefit from *Sphagnum* being re-introduced (Rosenburgh, 2015). Trials showed that the technique could succeed, that of the species tried, *Sphagnum fallax* performs best, that in areas of dense vegetation, flailing increases *Sphagnum* establishment and that water availability is key, with drought killing the propagules (Rosenburgh, 2015).

Techniques for restoring peat cuttings

Lessons learned at Thorne Moors for restoring peat workings (Money 1994) may improve cost-effectiveness at other similar sites. Growth of *Sphagnum* in flooded peat pits was significantly increased by phosphorus addition. Other levels of the cuttings were too dry for spontaneous revegetation and simply blocking drains in a peat field did not stabilize the water table sufficiently for rapid *Sphagnum* growth. Lagoon formation was thought likely to help stabilize water levels and encourage bog vegetation to develop as floating rafts. Deliberate reintroduction of *Sphagnum* encourages raft development with small pools and shallow water (<50 cm) most effective (Money, 1994).

Techniques for restoring fen peatland used for arable agriculture

A regenerating ex-arable fen was a small net CO_2 source (21 g C m^{-2} yr^{-1}) but was estimated to have reduced emissions compared to its former arable use by avoiding losses of 88 g C m^{-2} yr^{-1} (Morrison, 2013). Even fens in semi-natural condition emitted CO_2 in years with warm dry periods and keeping water levels high was needed to avoid large soil carbon losses as CO_2. A more adaptive water management strategy was needed to make regenerating fens net CO_2 sinks (Morrison, 2013).

Restoration costs in the current literature

Table 3. Restoration cost summary from published literature

Type of restoration activity	Average (£ per ha)	Median (£ per ha)	Reference
All restoration types combined	Euro1,200	880 or 1500 (including land purchase)	Chapman et al (2012) Holden et al (2008); Andersen et al. (2017)
Drain blocking (ha)	879 Ca. 250 306 490-1200 (higher cost includes monitoring)	517	Artz & McBride (2017) Moxey (2011) Grand-Clement et al (2015) Grand-Clement et al. (2013)
Hag Reprofiling (ha)	704	688	Artz & McBride (2017)
Restoring cutaway peat (ha)	300	No data	Wilson et al (2012)
Living mulch on bare peat (ha)	2976	1487	Artz & McBride (2017)
Forestry removal (ha)	2996	1480	Artz & McBride (2017)
Forestry mulching (ha)	2425	2425	Artz & McBride (2017)
Peat dams and reprofiling (km)	1000	1000	Artz & McBride (2017)
Hag Reprofiling (km)	99.3	66.6	Artz & McBride (2017)

Ecosystem service benefits

The following section is a brief overview of general observed benefits of peatland restoration projects. A brief description of the specific improvements for each intervention type follows, but overall, improved site wetness due to water tables closer to the surface; vegetation recovery (albeit often partial); reduced losses of carbon in gaseous and aqueous forms; as well as employment and visitor benefits, are the most frequently reported. It is unknown whether there is any significant bias in the monitoring and reporting efforts for the potential benefits.

Drain-blocking techniques have generally been observed to produce significant water quality benefits (Table 4), for example reduced discharge often combined with reductions in the immediate and short-term losses of carbon through significant reductions in both dissolved and particulate organic carbon. There are, however, some studies that show no change or increased losses of dissolved organic carbon and some authors have cautioned against extrapolating from short-term responses. Often, a benefit in terms of the average water table is observed (Table 4), however there are also some studies that did not find this to be the case (e.g. Wiliamson et al., 2017) or observed only very spatially limited effects (e.g. Holden et al., 2017).

Table 4. Observed ecosystem service benefits from peatland restoration efforts. Benefit categories are: F - full restoration to near-natural target, P- partial response, converging to near-natural target; N – none or insignificant response; D- decline or divergence from near-natural target; B – beneficial but not quantified against target reference point; ND – no data.

Restoration category	Ecosystem service benefit	References
Drain or gully blocking (bog)	- Reduced sediment load, DOC concentrations and/or colour (P/N), over short as well as long term, although some studies show increased DOC losses in the short term - Reduction in discharge (B), increased (relatively slower) overland flow (P), although occasional increases in discharge have also been observed - Reduced DOC export short term(P) - Rise in water table short term (N/P) - Prevention of decline in water quality (P) - Increased sediment load (D) - Increase in average water table (P/N), including effects observed adjacent to the drain, over short as well as long term, but can be limited in spatial extent in some circumstances. - Increase in indicator species, e.g. *Sphagnum* cover (P/N), increase in vegetation indicative or wetter conditions and decline of vegetation indicative of dry condition adjacent to blocked drains (P). - Recovery of aquatic macroinvertebrate fauna (P) - Insufficient data on GHG effects, though some suggest improved greenhouse gas emissions short term (N/P/D) - Limited data on agricultural productivity, thought not to be affected in terms of grazing carrying capacity (N) - Perceived negative effect on recreational use (D) due to wetter soil conditions but potentially beneficial effects for access for grazers (B) - Short term increase in released bromide in water (D), but no longer term studies published	Anderson et al., 2011; Armstrong et al., 2009, 2010; Bellamy et al., 2012; Brown et al., 2016; Cooper et al., 2014; Dooling, 2014; Gatis, 2015; Gibson et al., 2009; Grand-Clement et al., 2013; Green et al., 2017a, 2017b; Hannigan et al., 2011; Hughes et al., 1996; Holden et al., 2004, 2007, 2011, 2017; Martin-Ortega et al (2014); Peacock et al., 2015; Turner et al., 2012, 2013; Wallage et al., 2006; Wallage, 2007; Williamson et al., 2017; Wilson et al., 2010, 2011a/b/c; Wilson, Wilson & Johnstone 2011; . Worrall et al., 2007;
Drain blocking (fen)	- Recreation (B) - Grazing use (B) - Flood protection (B) - Reduced greenhouse gas emissions (B)	Hughes et al., (2016); Peh et al (2014)

Forestry removal (bog)	- Reversal of subsidence (P) - Additional surface water quality impacts in the short term after felling (D) - Reduced tick abundance (P) - Biodiversity benefits (B) - GHG emission benefits (P) - Aquatic carbon benefits (B) - Hydrological benefits (P) - Nutrient cycling effects (B) - Net carbon stock accumulation (P) - No long term impact on suspended solids (N) - Water table rise (P/N)	Andersen et al., 2017 and references therein; Anderson and Peace, 2017; Artz et al., 2013; Gaffney, 2016; Gilbert 2013; Muller et al., 2015; Murray, 2012 Yamulki et al., 2012;
Revegetating bare peat (erosion control/peat cuttings) (bog) Regeneration post-agriculture (fen)	- Reduced DOC, POC and lead fluxes (F/P) - Reduced leaching of inorganic N (B) - Fertiliser application may lead to increased aqueous P losses (D) in short term - Reduction in storm peak flows (B) at larger landscape scale - GHG emissions benefits (P), although rates of soil respiration increase after restoration (with bare soil having very low emissions), these are counteracted by increased photosynthetic uptake (which is virtually nil in bare site) - Microbial community composition recovery (P) - Water table increases (P/F) - Vegetation recovery (P) - Reduced DOC in water (N) - Increased aquatic carbon (N)	Clay et al., 2012; Dixon et al., 2014; Edopka et al., 2017; Elliott et al., 2015; Farrell and Doyle, 2003; Grayson et al., 2010; Morrison 2013; Qassim, 2015; Shuttleworth et al., 2015; Stimson, 2016; Stimson et al., 2017; Wilson et al, 2013; Worrall et al., 2011.
Scrub control (bog)	- Higher and more stable water table (B) - Biodiversity benefits (B) - Improved CO_2 sequestration (B)	IUCN (2010a/b/c)

Vegetation composition adjacent to blocked ditches generally shows little change (e.g. Green et al., 2017b; Williamson et al., 2017). Therefore, whilst off-site benefits are generally observed, on-site benefits appear more limited based on the data gathered to date. One possible mechanism for this lack of response could be an adaptive mechanism following the original drainage, effectively leading to a degree of 'self-rewetting' of the drained peatland over time (e.g. Williamson et al., 2017; Holden et al., 2016). Overall, very few studies have monitored effects for longer periods, even though some studies have observed that effects can change significantly through time after restoration is completed.

Revegetating erosion gullies has generally been shown to reduce peat losses in the suspended sediment downstream (Table 4). A notable result in this regard is the study by Shuttleworth et al., (2015) who showed that the stabilizing effect of revegetation led to reductions in DOC and lead fluxes to those comparable to an intact peatland in experiments conducted in the southern Pennines on a site where restoration began in 2003. Similarly, forestry removal generally shows positive benefits, with the possible exception of transient impacts on water quality immediately after felling (Table 4). To specifically assess the cost effectiveness of restoration projects in carbon terms, total carbon budgets (gaseous, aqueous and particulate carbon losses or gains) need to be assessed for each project. In some cases, proxies have been used, for example, the MoorFutures project in Germany calculated the net carbon gains of restoration projects using a standard methodology that relies on proxies derived from the GEST (greenhouse gas emission site types) approach. Guenther et al (2017) tested this methodology and found direct measurements of GHG emissions to be more reliable as the indirect methods generally underestimated the reductions in emissions due to restoration. Crucially, in more than half of the projects tested, the carbon benefits were significant, even if the additional cost of monitoring the emissions on site were taken into account.

Evaluation of cost effectiveness or cost-benefit ratios – possible approaches

Estimating the potential value of restoration projects where no tangible, sellable product with a market value is obtained, can be difficult. In this case, an estimate was asked for of the difference in ecosystem state due to the intervention compared to the counterfactual of no restoration. In this case, restoration aims to change the ecological state of a peatland to a 'better' state. It is possible to calculate the ratio of the cost of the intervention to the perceived monetary value of the change in ecosystem service provision, and so provide an indicative value of the cost-benefit ratio. The latter values are generally obtained via stated preference or "willingness to pay" surveys. Martin-Ortega et al (2016) carried out a survey of over 1,000 Scottish respondents, which suggested that the cost of the restoration interventions generally fell within the same range as the monetary value people were prepared to pay: £127 to £414 for a change in overall ecosystem condition from bad to intermediate, or intermediate to good. Glenk and Martin-Ortega (2018) then used these data to compare against current ranges of capital and recurrent restoration costs, and found that values were generally indicative of benefits exceeding costs. This positive societal perception of cost-effectiveness of these interventions is a very encouraging result. However, although their time horizon for the study was 2030, their analysis did not include an assessment of whether people were prepared to pay the same amount irrespective of the time it would take to achieve such a step change. In other words, it was not assessed whether people were equally likely to pay the same sum for achieving the restoration goal of recreating a peatland in good condition after 10, 20 or 50 years. This may be crucial because current evidence suggests (as summarized above and in Table 4) that the majority of restoration projects do not achieve the state of near natural peatland after 10 years. Similarly, the risk that such projects could fail altogether was not assessed. Future work carried out in the RESAS Strategic Research Programme includes assessment of preferences for peatland restoration up to 2080 (Glenk and Faccioli, pers. Comm.)

Other approaches have assessed restoration costs against the likely carbon benefits, as these are relatively straightforward to calculate if the emissions reductions have been monitored. Even with the early analyses of carbon abatement potential, which suffered from a relative lack of published data on greenhouse gas and other emissions from near natural vs damaged sites, it was evident that there were significant carbon benefits in peatland restoration efforts (Chapman et al., 2012; Artz et al., 2012; Worrall et al., 2009, 2010). This led economists to compare the relative costs of such interventions and their GHG emissions mitigation potential against other policy instruments (e.g. Moxey and Moran, 2014). Moxey and Moran (2014) considered peatland restoration as a cost-effective method on average, based on published ranges of the upfront, capital costs as well as recurrent, maintenance costs when scaled against the non-monetary biodiversity benefits as well as appropriately discounted net emissions abatement likely to be achieved. Unfortunately, they were unable to calculate these ratios for any case studies, as there were no sites in existence where all of the input parameters required for the calculation had been monitored. This was especially true for the monitoring of acheived emissions reduction and remains so to this date (Artz et al., 2015). As emissions monitoring is relatively complex and requires staff time as well as equipment, maintenance and data analysis costs, proxies for emissions reductions have been used in many countries that include the average emissions observed on different condition or primary vegetation types (e.g. the GEST approach in Germany; Couwenberg et al., 2011). However, it is worth noting that Guenther et al (2017) calculated the cost of monitoring emissions on peatland restoration projects in Germany directly and found these to be cost-effective in the evaluation of the effectiveness of the work. Moreover, measuring emissions on site was found to be a better estimate of the achieved carbon benefits as the proxies tended to underestimate the achieved reduction in emissions. As restoration providers' experience and access to equipment grows, the capital costs required to undertake such projects may fall, and in some cases, this has been demonstrated already (Birnie & Smyth, 2013). The same may be true for recurrent costs, both via technological advances on the ground but also through the potential use of remote monitoring (Moxey and Moran, 2014); however, no case study examples of this were found in the literature. Increases in costs, however, are also possible, via increased labour costs, land prices, or higher subsidies/income form land. Similarly, we are unable to find case study examples in the literature that examined these through time.

These positive reports led to the development of a voluntary market for peatland restoration via the UK Peatland Code and analogous instruments elsewhere. Reed et al (2017) summarised a number of Peatland Code projects which agreed fair prices ranging from tens to over a hundred pounds (£) per tonne carbon dioxide equivalent achieved. One aspect that is generally less well considered is the long term viability of peatland restoration projects, where potential loss of income (income foregone) may play a crucial factor in the decision making process. Moxey (2016) considered the eligibility of land post-restoration for CAP payments and found that there was generally no immediate threat to continued payments if the land was still deemed to be agriculturally active. This could be taken to mean a low stocking density, especially if it could be proven that there was historically low carrying capacity. However, displacement of stock, and grouse, on such areas was generally considered to be detrimental, especially given that the profitability of such businesses was already considered marginal. In addition, the UK Peatland Code at present does not yet consider long term risks to restoration projects, such as damage through accidental or wildfire, or indeed adverse climates. These are largely ignored in the literature so far. Finally, there have been some attempts to carry out analyses of the costs and benefits of restoration processes against an alternative state. One example of this is the Wicken Fen Vision Project, where the fen restoration project was compared with the realistic alternative state of ongoing intensive agricultural use of nearby fens. Although the restoration goal at this site is not to re-create a fully functioning fen in the short term as this is unrealistic, despite the somewhat 'open end goal' of the project, several services were identified as having increased due to the restoration work (Table 4, Hughes et al., 2016; Peh et al., 2014). In this particular case, the service lost was in the production value of the land. Further monitoring to ascertain the effects on other components of ecosystem services (biodiversity aspects, connectivity, water regulation, recreational use etc.) is ongoing (Hughes et al., 2016).

Analysis of peatland restoration projects since 2010.

We analysed the full dataset of completed Peatland Action projects to date (n=150) for trends with regards to altitude, distance to nearest road and nearest urban centre (Figure 1,2). The resulting chosen 30 sites for follow-up in our survey were selected to ensure as close a representativeness of the original population as possible (Figure 1,2). A further two sites that have been restored in Scotland since 2010 through alternative means of funding were highlighted through communications with statutory agencies and the UK Peatland Code team.

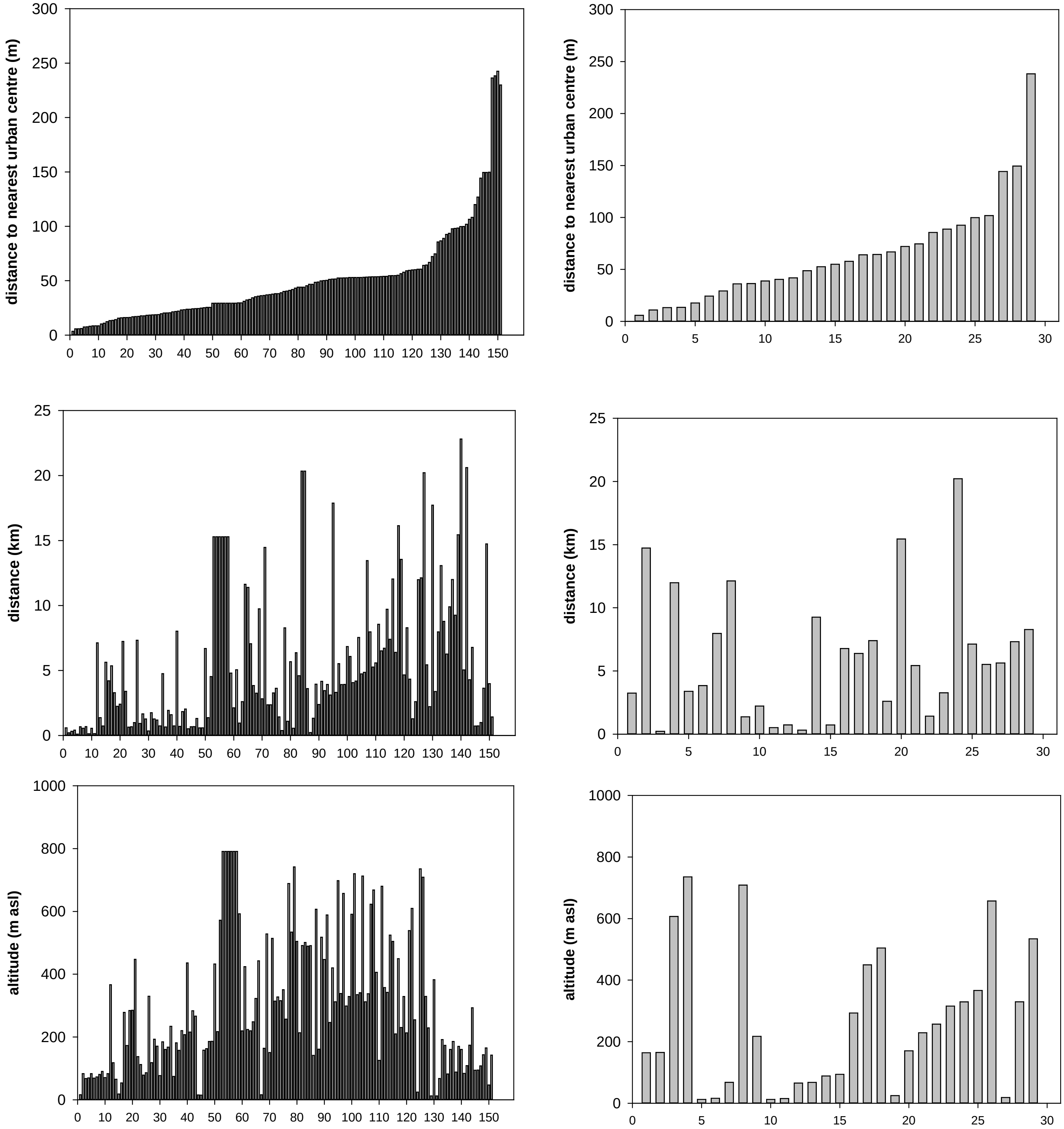

Figure 1. Characteristics of the 150 Peatland Action projects completed until April 2017 (left figures) and the 30 selected case study sites out of the total (right figures). Data are presented in order of the site overall distance by road to the nearest urban centre or major town, in miles (top row). The middle row presents the site centroid distance to the nearest metalled road in km (middle row), and the bottom row shows sites in terms of their altitude (m above sea level. The order of sites in the middle and bottom row is the same as for the top row.

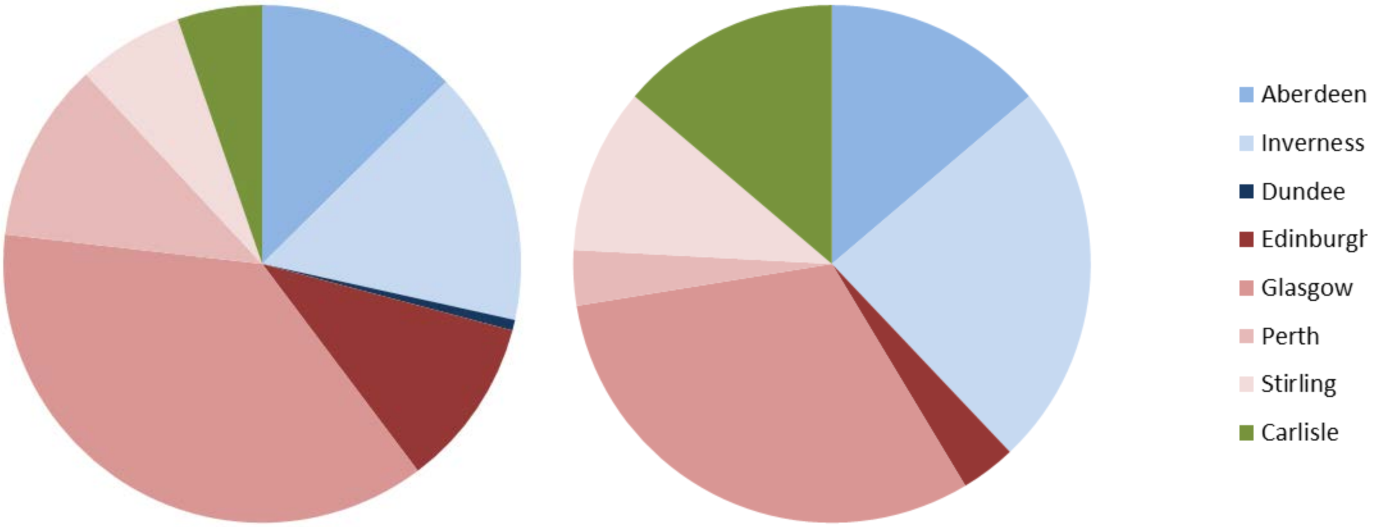

Figure 2. Proportion of sites closest to towns/cities in Northern Scotland (Inverness, Aberdeen, Dundee, in blue), Central Scotland (Edinburgh, Perth, Stirling or Glasgow, in red), or Northern England (Carlisle, in green), apportioned by shortest distance to urban centres , respectively, for all 150 Peatland Action sites completed before April 2017 (left) and the sites shortlisted for the online survey (right).

Survey uptake and follow-up rate

The shortlisted sites were submitted to SNH's Peatland Action team for consideration and were largely adopted for follow-up. The Peatland Action team provided contact details for the PA officer and grantee for each individual project and made first contact. A further 2 sites out with the Peatland Action project were contacted directly by the project team. 21 out of the 30 Peatland Action project grantees, 1 Peatland Action officer that was not acting on behalf of the Grantee, and 1 out of 4 identified contractors gave consent and agreed to complete the survey. A further 2 out of 2 of the non-PA project leads agreed to complete the survey and gave explicit consent. Not all people were able to complete the survey in time. In total, we received 20 completed surveys and three additional incomplete surveys. 2 out of the completed surveys contained additional information by the relevant contractor and Peatland Action officer for a site already covered, respectively, resulting in data from a total of 18 restoration sites. The information for two out of the three incomplete surveys was too limited to be used for the data analysis, and the last of these did not include broken down cost information and so could only be used for the assessment of ecological benefits and total project cost.

General characteristics of the sites included in the survey

The majority of the peatland restoration projects (15) included a drain or gully blocking intervention aimed at rewetting the site (Figure 3). A total of 5 projects each included erosion control and seven included forestry removal, whilst only three of the projects included scrub control as an intervention. On many sites, more than one intervention and/or more than one technique (Appendix 3) were used. Amongst the seven projects that included some other intervention, one included the respacing of transitional wet woodland in this category. Two projects returned under the 'other interventions' category included mulching and/or reprofiling and cross-tracking on a previously felled former forestry area, which presumably could have been categorised under rewetting activities but we didn't receive enough detail to be sure that this was the case. Two further projects mentioned re-vegetation. Others included site supervision or track repair under this category.

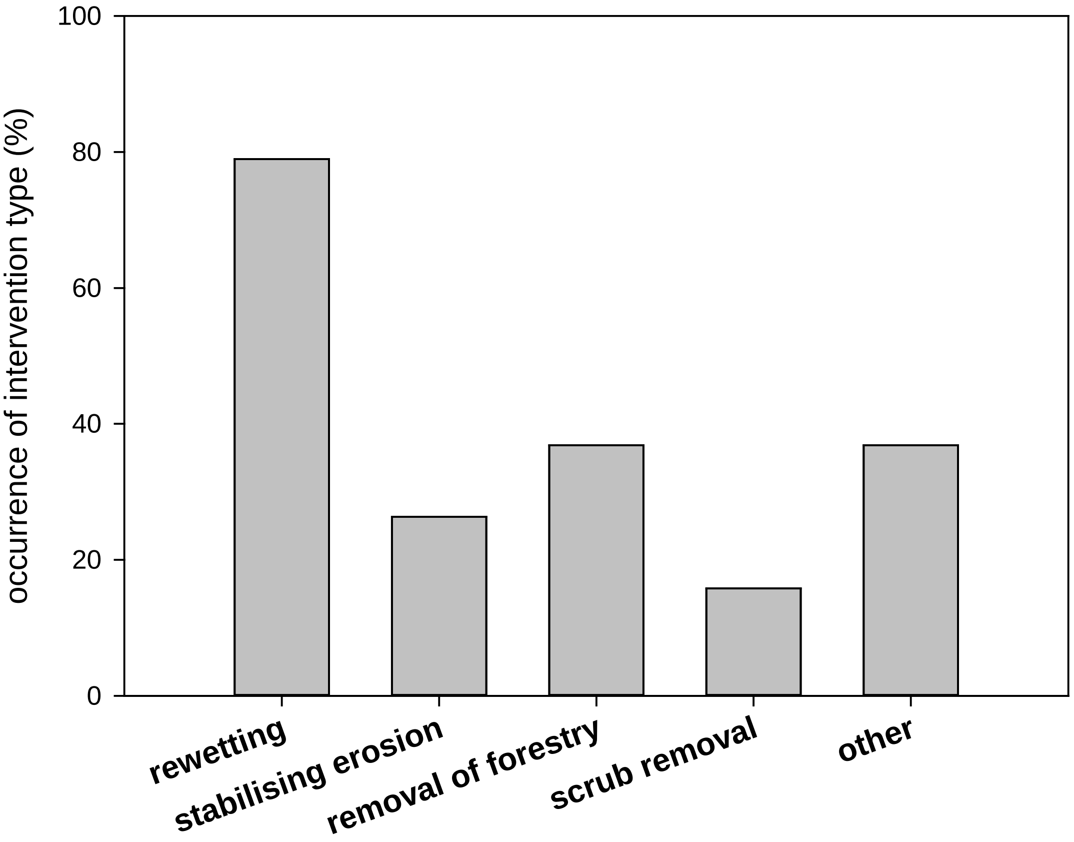

Figure 3. General characteristics of the restoration interventions carried out at the 18 sites with complete survey information and 1 incomplete survey. Some projects had multiple interventions, hence the total adds up to more than 100%.

A total of 6 out of the 19 sites (31%) had received prior restoration activities on the same sites, these ranged from prior scrub control to sites felled to waste in the past and areas where drain blocking had been attempted some time ago but had largely failed. The total area restored for these 19 projects was 642 hectares (sum of estimates), and an additional 60 km of drain or gully blocking/reprofiling where the survey respondents were unable to translate these into area units. Several survey respondents flagged up a lack of a standard methodology to assess the area restored where drain blocking or gully blocking/reprofiling was considered.

Half of the survey respondents said that specialist machinery was required to carry out the intervention. The forestry removal projects required harvesters, in some cases adapted for the soft ground. Several of the drain-blocking projects specified the need for a low ground pressure wide tracked excavator. One mulching and flailing project specified the need for a low ground pressure vehicle mounted with a revolution cutter wheel. Some *Sphagnum* spreading trials used a specialised low ground pressure tractor with adapted fertiliser spreading bucket. More than half of the respondents (55.5%) said that specialist skills were required. These included previous experience of working soft sites with excavators, chain saws and harvesting machinery, experience of felling trees parallel to and between each of the drains thereby keeping each drain clear of material, and prior experience of herbicide application to Industry standards. Reprofiling work required knowledge of how to move peat turves to create a non-eroding surface. Several people also mentioned that contractor skills have co-evolved with the land manager communities over the past, as restoration techniques have been improving.

Calculation of cost-effectiveness and other data analyses

All of the 18 completed surveys and one of the incomplete surveys returned total project costs. Total costs for these 19 projects ranged between £3,576 and £190,984, with a total spend on the projects of £1,078,566. Unfortunately, many of the survey returns carried inconsistencies as the calculated total based on the breakdown exceeded the stated total spend, or broken down costs were not provided. The survey structure did not allow people to simply input the invoiced cost per unit restored, which should be added to future survey repeats. We obtained this information via follow-up emails and telephone calls. Despite consistent efforts, invoiced costs per hectare or kilometre restored were not returned for all surveys, with only 10 of the projects giving this information. For another 7 projects, the broken down costs were estimated as closely as possible with the information given. Average costs were generally within £800 to £3000 per unit (Figure 4), with the exception of erosion control costs. We were unable to calculate a reliable figure for the costs per hectare of erosion control as the four figures received varied by three orders of magnitude. The reasons for this discrepancy may be in the exact detail of the work completed, for example, the two projects with costs in the tens of thousands of pounds per hectare both used translocation of vegetation in their sites. This suggests that, in order to gather reliable figures on the cost of erosion control, further follow-up is required. The same applies to the single observed value for erosion control per km restored and the two figures returned for scrub control. These values should therefore be viewed with caution. In addition, a number of projects reported that a higher budget than anticipated was required to complete the work, in some cases the landowner put in additional in kind contributions or where the SNH contribution of the Peatland Action officer was not included in the costings. We included these costs where estimates were given, however this information was not always provided. There were also some survey returns that suggested that the contractor had underbid in order to win the contract but then had to finance completion of the work themselves.

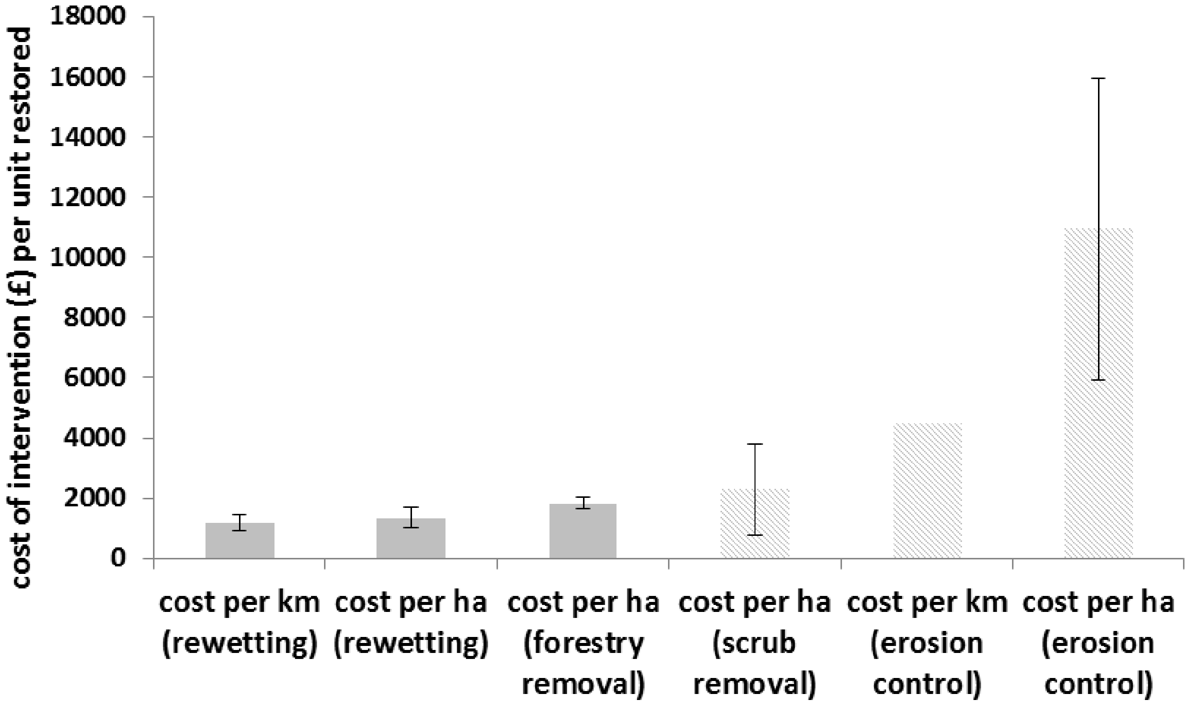

Figure 4. Costs per unit restored, based on 17 completed responses (10 responses with direct cost information, 7 responses where costs had been calculated as a best estimate based on information given). Numbers of observations for individual categories are as follows: rewetting (11), stabilising erosion (5), removal of forestry (5), scrub removal (2). Patterned bars represent categories where data were insufficient to calculate robust average values. Other interventions, e.g. track construction etc. not shown. Individual observations exceed number of sites due to multiple interventions in some locations.

Cost-effectiveness analyses generally compare one intervention against an alternative option, such as to "do nothing" or to use a different intervention. In restoration efforts, there is often no suitable "do nothing" control as individual sites where work is intended are only very rarely split into control and intervention plots. It is also difficult to assess the relative cost effectiveness of one restoration intervention against another, due to the sheer number of possible restoration methods within each primary intervention type (Table 1). In our study, we found that there was little replication of individual techniques between the completed surveys to date (Appendix 3). It must be noted that we did not have cost information for all of the interventions reported; hence the number of reported techniques exceeds that of the costed interventions above. Amongst forestry removal techniques, there were several that employed felling to waste, but we found no useable replication amongst alternatives such as whole tree mulching or whole tree harvesting. One survey that was a forestry removal project (token 14) did not specify which techniques had been used. For rewetting drained peatlands, we had 13 out of 15 sites using damming of drains with peat dams, but a maximum of four replicates for damming peat using plastic and no replicates for other techniques. For scrub and bare peat/erosion control, we had insufficient survey returns (3 and 5, respectively). Most of the projects (15 out of 19) utilised multiple techniques on each sites, with a maximum of 4 (Appendix 3) and many returned surveys indicated that multiple primary interventions (e.g. forestry removal and drain blocking in an adjacent area) had been carried out. This observation caused difficulties in the calculation of cost-effectiveness, as these costs were often not provided as broken-down costs.

In principle, however, it should be feasible to determine whether interventions in certain situations have a lower cost-effectiveness than other. For example, it might be possible to employ regression analyses to explore contrasting (i.e. low versus high) altitude, or sites closer of further away from a major urban centre. For the purpose of this pilot study, we designed the sample of sites so that a small minimum number of replicates for each of these contrasted groups should have been available if survey return had been 100% (Table 2). We also included island locations, however the numbers of these were deemed insufficient to calculate contrasting cost-effectiveness ratios, and hence these were bundled under the distance to nearest urban centre contrast (Table 2). We defined the classes as follows:

Class/contrast group	Low	Medium	High
Distance	0-40 miles	40-75 miles	>75 miles
Altitude	Below 200 m asl	N/A	Abo ve 200 m asl

Table 2. Minimum expected number of observations per contrast group as per original survey design for the 30 test sites. The final number may be considerably higher as many PA projects include multiple primary restoration activities.

	Contrast		
Primary restoration activity (number of sites surveyed in brackets)	Distance to nearest urban centre (low-medium-high)	Altitude (low-high)	Nearest urban centre location (North Scotland-Central Scotland-Northern England)
Rewetting (12)	4-4-4	7-5	2-7-3
Forestry removal (6)	2-2-2	3-3	4-2-0
Scrub removal (6)	4-2-0	5-1	2-4-0
Erosion and bare peat cuttings control (6)$	0-4-2	2-4 ($)	4-1-1

($) The erosion control contrast on the basis of altitude may be problematic as erosion tends to happen in the uplands, whereas peat cuttings are generally at lower altitude. The resulting difference in starting condition may influence outcome, despite the generally similar technical restoration methods.

Differences due to altitude or distance from the nearest urban centre could only be explored in the sites where rewetting and forestry removal had taken place, due to the low number of survey returns for erosion and scrub control (Figure 5). We would have assumed that rewetting and forestry removal costs would have been higher per unit restored at higher altitudes and at greater distances from an urban centre, however the data do not suggest such a trend. It is possible that distance to the nearest urban centre is not a good measure of the contractor cost calculations, as it will be dependent on the access route for the contractor (i.e. they may be located closer or further away than the nearest urban centre). Some may perceive indications of a slight upward trend in the few obtained values of forestry removal costs per hectare with increasing altitude; however this is most likely a co-incidental finding as the average costs of forestry removal per site masked internal variations within each site in the proportional cost to remove denser or less dense conifer stands. These differences in cost are in the same range (£765-3450 per ha for low-high density stands) as total average variation in costs in Figure 5. As we were unable to check the effects of stand density (data were not asked for in the survey), no conclusion should be attached to the apparent increase of costs with altitude.

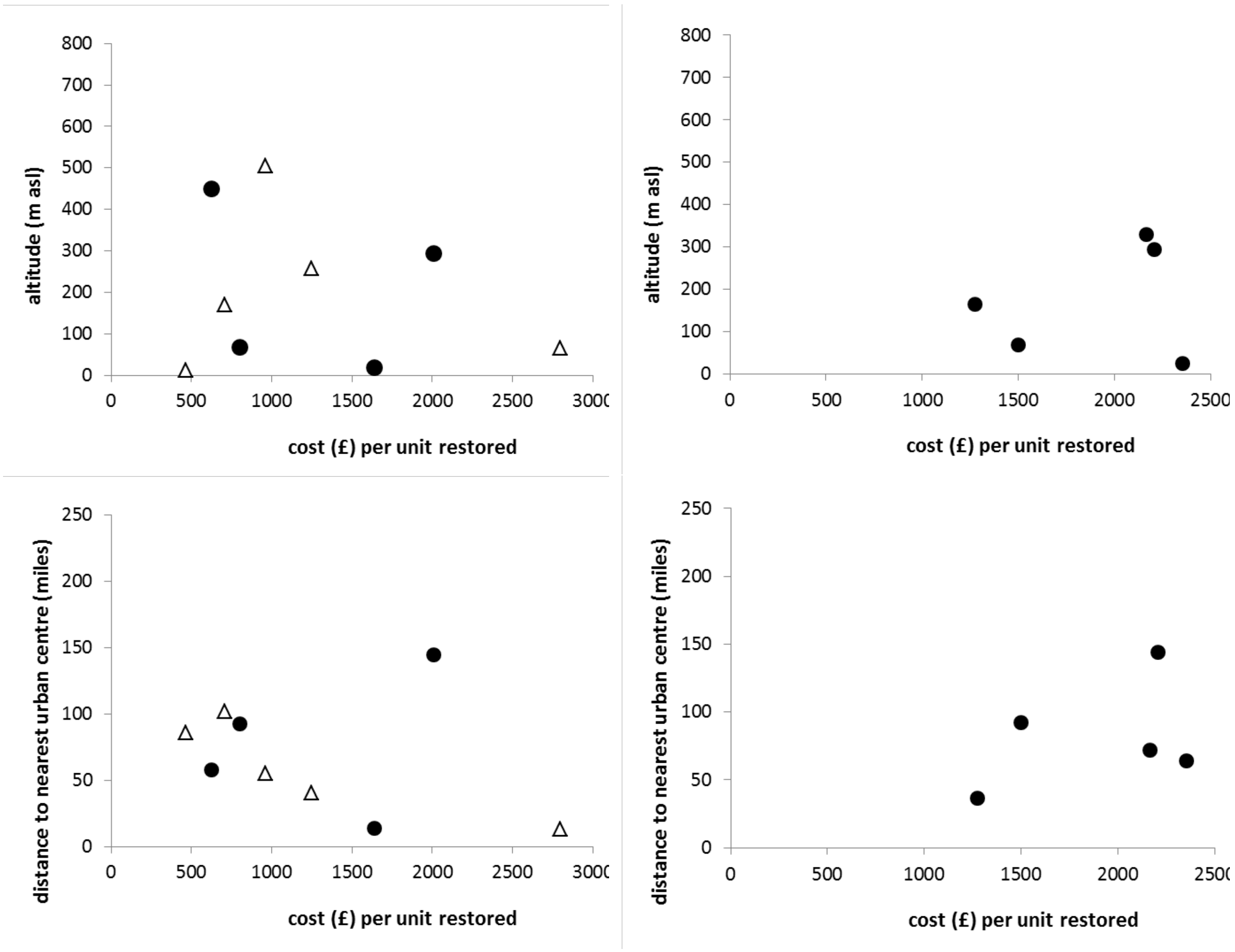

Figure 5. Differences in cost-effectiveness due to altitude (top row) or distance from the nearest urban centre (bottom row) for rewetting (left, filled circles for costs per km drain or gully; open triangles for costs per hectare drained land) and forestry removal (right) interventions.

Effectiveness on its own (i.e. without the cost aspect) could be considered in several ways: at the simplest level, a question was asked about whether the project delivered the expected activity in full. This could be expressed as a proportion, e.g. if only 80% of the intended area was rewetted, the effectiveness was 0.8. We also considered the ecological effectiveness within the year of project completion in a similar manner. Finally, we asked for the perceived likely need for further intervention before 2030. Figure 6 shows that, generally, average effectiveness was 100% of the expected work immediately after completion, and in some cases (e.g. erosion control projects), a larger area or increased length of restoration was completed than planned. Effectiveness after one year was also generally nearly 100%, with the exception of erosion stabilisation, where there was an average 20% failure rate in the areas restores amongst the projects surveyed. Finally, the respondents gave their opinion on how likely they felt it would be that further work would be needed before

2030, and all interventions were thought to require further work by this point, although the highest perceived need was for seedling regeneration control in ex-forestry sites and areas with scrub encroachment.

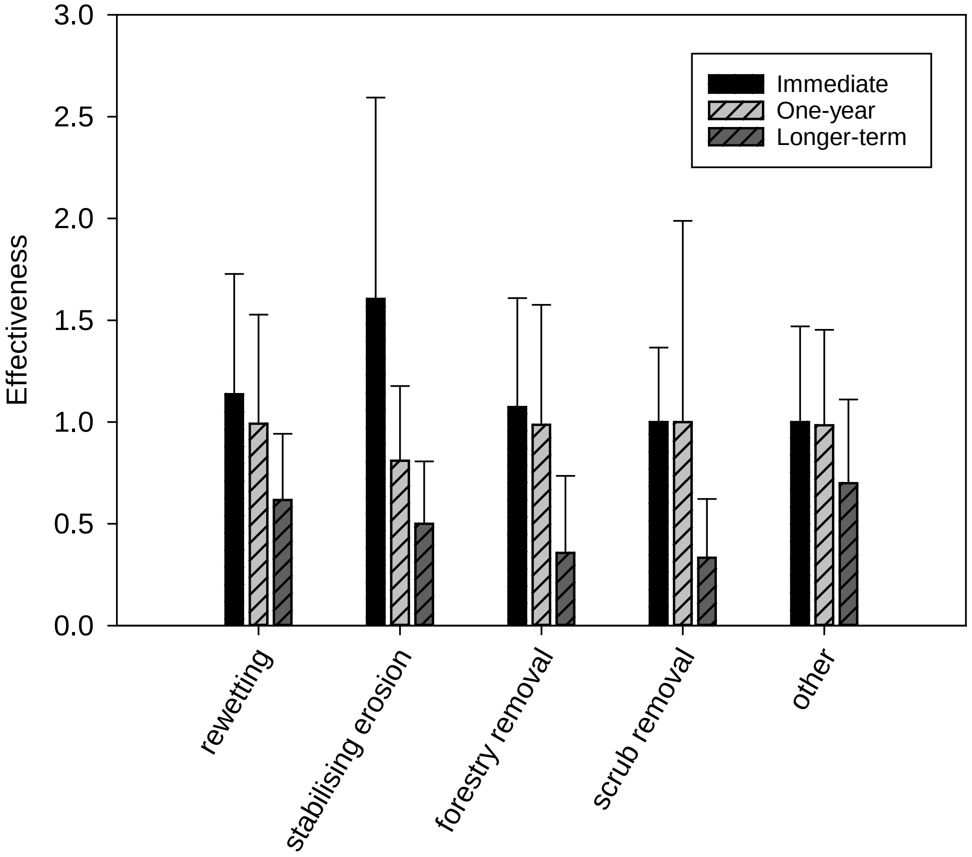

Figure 6. Perceived effectiveness of the restoration intervention types, based on 19 completed responses. Numbers of observations for individual categories are as follows: rewetting (15), stabilising erosion (6), removal of forestry (7), scrub removal (3), other intervention (6).

Ecosystem service benefits

Almost all returned surveys to date suggest high perceived ecosystem service benefits (Figure 7), with the majority of the results showing a range of perceived positive impacts across at least part of the site (score of 1) to perceived noticeable positive impacts across the whole site (score of 3). A very small number of respondents (1 each) rated the aesthetic impact of rewetting, scrub removal and erosion control to be slightly negative across at least part of the site. On average, peatland restoration efforts were effective at delivering several positive ecosystem service benefits. One possible limitation of the approach may be that asking respondents to report on observed benefit at a potentially much later time could be problematic as there is no true measure of the expected benefit *at the time points considered*. Our approach can only ask for this information in retrospect, which may colour perceptions of the observed benefits at the time. In addition, a couple of respondents were unsure whether aesthetic assessments would hold true for different observers.

Only 9 out of the 19 projects have some form of water table monitoring, however two of these were only on the basis of visual or photograph assessments. The majority of the remaining seven respondents did not have access to the water table monitoring data, but two sites were noted to have shown improvements in the water table based on data collected to date.

All interventions were generally reported to have been very effective. Some of the qualitative comments have been summarised in Box 1.

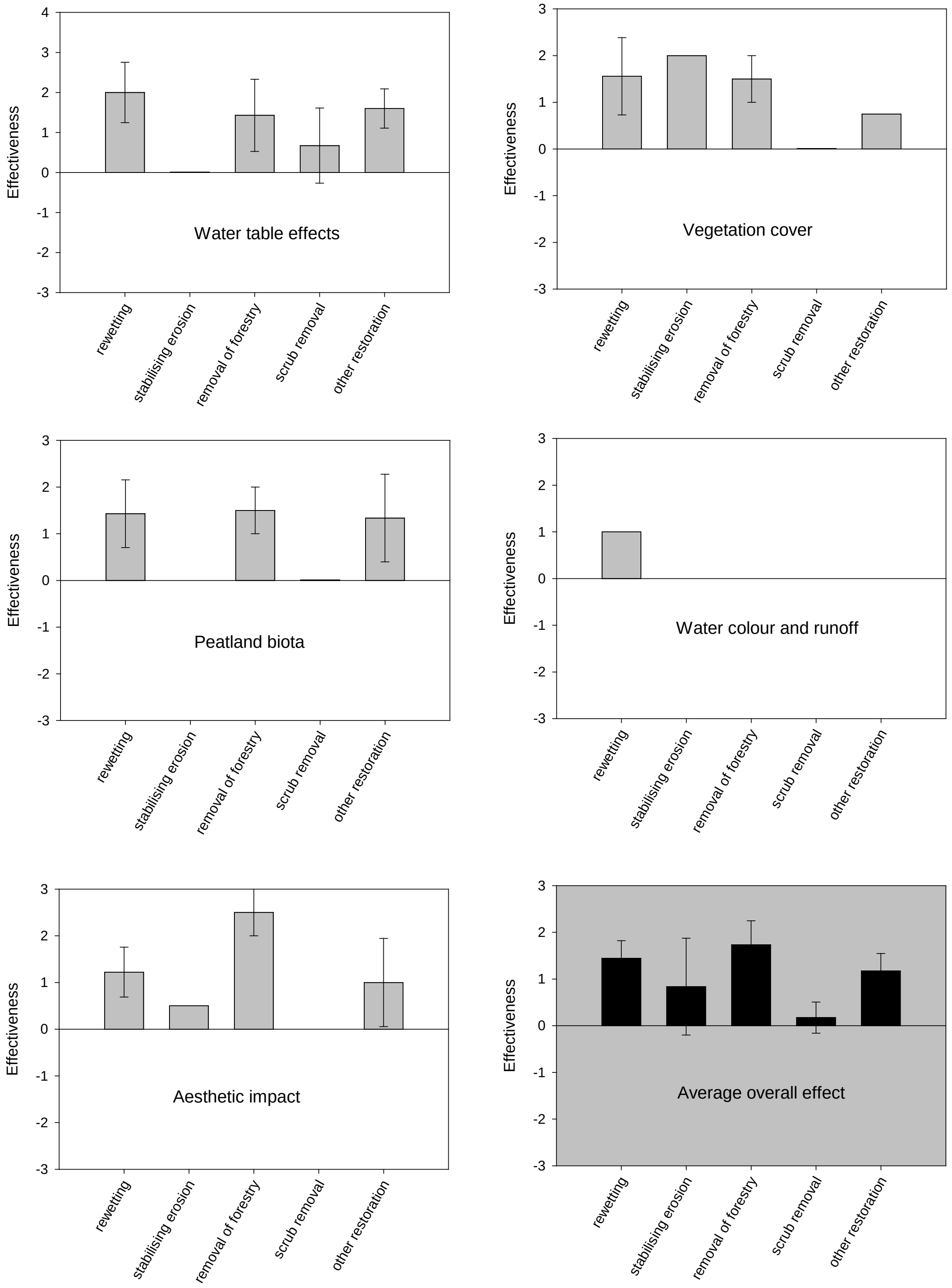

Figure 4. Perceived ecosystem services benefits of the restoration intervention types, based on 19 completed responses. Interventions deemed to be positively beneficial would score above 3 on the scale, with complete success across the whole site scoring as 7. Numbers of observations for individual categories varied as respondents had the option to skip the questions Individual measures of ecological effectiveness were water table or surface wetness responses (top left), changes in vegetation cover (top right), changes in species complement (middle left), changes in water colour of runoff (middle right), aesthetic change (bottom left) and the overall ecosystem service benefits (bottom right). One response on the aesthetic effectiveness of scrub removal was deleted due to two mutually exclusive options having been ticked.

Box 1: Comments received by survey respondents on the effectiveness of the restoration efforts.

“Ditch blocks appear solid. Tree regen unlikely to be removed during this time frame.”
“Restoration appears to have been done well. This has since been assessed by SNH and there appears to be no need for additional maintenance”.
“It is unlikely that further forestry removal will be required by 2020 although tree regeneration is likely over a longer timescale on the ridges of plough furrows. Rhododendron ponticum is recolonizing the site rapidly and clearance would be required before 2020 to maintain the benefits of restoration efforts.”
“Re-wetting: All peat dams created were holding earlier this year and the site was re-wetting well therefore I would see no reason to carry out additional works. Forestry removal: As of earlier this year there was little to no sign of Sitka regen on the site. I'm sure there will be some requirement to deal with it in the future, but not in the next 3 years."
“Some future maintenance may be required depending on the weather immediately after restoration and how it affects stabilisation.”
“The long term success will be improved if stock could be kept off or away”
“Conifer regen certain to continue for a number of years, particularly on forestry removal schemes. Seed sources will gradually be eliminated as further sites are cleared and restored. Some maintenance also likely to be required ensure drain blocking work remains effective. Ground smoothing and furrow re-profiling may also be required on ex forestry sites but often better done several years after felling once brash has broken down.“
“Successful as initial operation, but further work e.g. ground smoothing required to result in hydrologically function bog at surface; bog habitat developing primarily in plough furrows but not ridges.”
“To date, no areas have failed.”
“One small peat dam is leaking, it could do with a plastic piling dam to reinforce. Alot of the veg has taken well but one area is proving difficult to get established. Re-profiling technique was a bit patchy in places.”
“Some of the spread sphagnum was blown off the site after spreading so instead of complete coverage there is approximately 50%.”
“There are a couple of small leaks that are associated with the retro fitting of twin wall pipe to control the water level in some cells.”
“For both activities in following years some restoration work had some areas of failure. Some of the areas where dams were installed have had wash-out at the side of the dam. This has resulted in some higher flowing water continuing to erode the peat. In some areas this geotectile membrane has disintegrated before vegetation recolonised the bare peat resulting in no improvement to the condition of the peat. The lack of re-colonisation appeared to happen on the more exposed areas.”
“Most of the dams are still holding 3 years later, but some dams have failed. This might be due to poor dam construction, or to heavy water loading behind the dams. There's not many dams that are no longer functioning.”
“On rare occasions some peat dams do not hold water as well, but still having a positive effect.”
“It takes a long time for vegetation to recover, sheep grazing.”
“Restoration so good not easy to tell where hags had been!”
“We now have peaty pools across the bog area and the ditch lines are starting to disappear due to vegetation build up, but this will take a long time to achieve vegetation change across the whole restored area.”
“Bare peat virtually eliminated from the site.”
“Visible water stress on remaining trees suggests increasing water table.”
“An unexpected result from the restoration was dominance of Molinia rather than more desirable bog vegetation. Possibly due to disturbance effects coupled with nutrient availability from forestry brash and stumps.”
“Some hags reprofiling has failed as it was done too steeply.”
“Plastic used was not as robust as previously used plastic so some plastic dams failed and some plastic pilings cracked when volunteers tried to bash them into the peat, resulting in a lower dam than required for restoration.”

Only a very few survey returns specified the breakdown of the costs to capital expenditure (6), labour costs (10), operating costs such as fuel and materials (2), and unforeseen costs (2). This was because the grantees and Peatland Action officers generally did not have access to this level of information on the actual spend, it was the contractors that would have held this information but we did not receive sufficient responses from this community. It was not possible to carry out in-depth analysis on these sparse data, and hence only some preliminary observations on labour costs can be included here.

Ten of the completed surveys included partial data on the number of days of paid staff time and day rates. A total of 241 paid staff days, ranging from 5 to 60 days between these ten projects, were required at an average cost of £220 per day. In addition, two of these projects specified a total of 82 days of unpaid workers at an estimated day rate of £100, although the cost estimate was only given for one of these projects. Due to the relative paucity of data, it is unclear whether manpower is a significant component of the restoration projects.

More than half (55.5%) of the respondents mentioned unforeseen issues that partially delayed the work. Amongst the reasons given were, in order of decreasing number of times mentioned: adverse weather conditions, access being too complicated, inexperienced contractors, retrieving equipment stuck in the peat, and changes to equipment required during the work. Some additional costs that had not been factored in were also mentioned. One out of 18 sites required additional surveying, two projects required additional staff or volunteers, that had not been costed in and three projects mentioned that the land owner put in significant extra in-kind contributions in terms of labour costs to supervise the project, but also in one case to carry out track repair costs. Therefore, as already alluded to earlier in this report, the calculated costs per unit in Figure 4 may not in all cases equate to the full economic cost of the work.

Three out of the 18 completed surveys said that there had been some income foregone, in all cases this was due to early or break-even felling of conifer. This income foregone is not just the value of the crop, as the market value of conifer plantations is higher than open blanket bog. Unfortunately, our survey returns were insufficient to calculate reasonably accurate estimates of the income foregone in this scenario.

Additional benefits in terms of increased staff or volunteer expertise through training and that could potentially benefit future restoration projects were mentioned in seven out of 19 surveys which returned this information. In most cases, this applied to a small number of people, who received training in specific peatland restoration techniques, vegetation surveying skills, or dipwell installation; however a small number of projects also trained a significant number of volunteers. For those three projects that mentioned numbers of volunteers trained, this ranged from 12-43 people.

Investment in additional staff or equipment was mentioned in only four case studies. This predominantly took the form of additional equipment or employment of clerks of works or ecological survey staff.

Finally, we asked whether the respondents thought that contractor costs had changed in the last 5 years. Eight people answered this positively, and the other 11 negatively. Out of the people who thought that contractors charges had changed, half thought they had declined (due to competition and higher skill level) and the other half thought they had increased (due to inflation). Fourteen out of 19 respondents thought contractor costs would likely change in the future, with most of these (12 out of 14) estimating costs to increase, largely due to inflation, increases in fuel prices and labour costs, but also due to a perception by some people that there have been some inexperienced contractors involved in some of the projects surveyed, who would be able to price their work more accurately in future. This reflects a growing market, where new contractors underbid in order to get a contract and gain the necessary experience for future work.

Some final comments by the respondents were in relation to the timescales and eligibility of items of work within the Peatland Action project. It was felt that the timing of the application deadlines and the requirement to complete work within the same financial year “make implementation difficult especially for larger projects”. Others mentioned that ineligibility of fencing materials made the long-term success of some projects less likely as the grazer density is perceived to be too high.

6. Discussion and Gap analysis

Peatland restoration activities are beginning to be assessed in terms of the effectiveness of the techniques applied to deliver the desired immediate result, as well as the effectiveness to deliver the long-term desired outcomes of a fully functioning peatland or a related semi-natural state if full restoration is not deemed feasible (e.g. Peh et al., 2014; Hughes et al., 2016). Whilst we did try to assess the effectiveness of the techniques to deliver the desired immediate result, due to the limited scope of this project, our pilot study did not assess the full suite of potential ecosystem services that may be affected by restoration efforts in Scotland, and instead we chose to focus on a suite of five components of ecosystem services (encompassing regulation, cultural and provision services). Our survey results did suggest that peatland restoration delivers positive ecosystem service outcomes for the five services we assessed. One limitation of our work is that these assessments were not done routinely at the end of each project, or a year after the work had been finished. The new tranche of Peatland Action funding does now require an assessment of visible changes that include some of the services we assessed, as well as others, as part of the final reporting form, however, there is no standardised assessment scale for these and hence comparison between similar projects would still not be feasible. Further work could also be performed, for example, to ascertain the monetary value of these five services, however this would require quantification of the benefits observed first. For example, whilst the cost of water treatment for drinking water to reduce DOC and POC is obtainable from e.g., Scottish Water officials, further work would be required to quantify the effects of the restoration activities on the water quality at the nearest drinking water abstraction point. This would also require apportioning of the effect of the restoration, and hence would probably only be feasible in controlled studies with a suitable baseline of data before restoration began.

A crucial limitation of the data we received was the oftentimes lack of an area estimate that had been restored. In other cases, it was not clear how this figure had been derived, and further follow-up would be required to ascertain whether the area affected was calculated with a comparable methodology between different projects. The new final reporting form now asks for the total area affected by the restoration intervention but there appears to be no standard guidance document to help grantees produce the required figures. A final limitation of our survey was that, in some cases, respondents had not been involved in all aspects of the projects, or had since moved to other jobs, so found it difficult to complete the survey.

In calculating cost-effectiveness ratios, the availability of sufficient and good quality information on the project results and associated costs is crucial, so data collection is an important step. In our exercise, we unfortunately only collected a relatively small number of completed surveys (especially from contractors) despite initially high willingness to contribute. The complexity of the survey instrument may partly explain this low response rate, however we also had difficulties in obtaining contractor contact details and very few replies from those we were able to contact. However, such complexity was required to collect detailed information about the merits and costs of different restoration projects, at the level of different activities and for different peatland typologies, to enable us to perform richer and more informative cost-effectiveness calculations than would have otherwise been possible. Despite the need to collect detailed data, we tried to minimize the burden on participants. We presented questions in a ‘chained’ way – i.e. respondents were only shown those questions that were relevant in relation to the characteristics of the restoration project. In addition, questions were targeted depending on the ‘type’ of respondent, with contractors being asked only about project costs and limited outcomes, and PA officers additionally asked also about pre- and post-restoration conditions of the peatland, and more detailed information about the project results or previous activities being carried out on the site (i.e. monitoring or other restoration), etc. One major limitation of our approach, which was necessary due to the lack of any common monitoring protocol across peatland restoration sites in the UK, was that we had to rely on perceived effectiveness, rather than a standardised measure. This may introduce bias due to differences in what individual observers may call ‘significant improvements’, for example. Future peatland restoration projects should consider adopting a common protocol for recording changes in ecosystem service delivery, to enable a more robust evaluation of the cost-effectiveness of such projects.

In calculating cost-effectiveness ratios, one important challenge is to correctly ‘apportion’ the stream of costs to the corresponding stream of benefits. This is not always easy to achieve. Cost aspects were often not available and were estimated on a total project cost (e.g. the contractor didn’t specify broken down cost by intervention). The new final reporting form for the Peatland Action projects does now specify that cash and non-cash costs have to be returned after completion of the work, however the form asks for these to be provided on the basis of different sites within each project, not for each intervention type. This may mean that some of the more complex projects, where multiple interventions take place on each site, will not be yield useable data for future cost-effectiveness or cost-benefit analyses. Our experience was that the most straight-forward route to this information was invoiced information itemised by restoration technique as well as site. We believe this is worth considering in future. It is also important to consider at what point in the restoration process cost-effectiveness is assessed. Similar to the cost-effectiveness of e.g. medical interventions, an intervention may be highly effective in the short-term but further management may be required to maintain the achieved state. Conversely, an intervention may not immediately seem to be very effective, but works by changing the trajectory of the site to a new future end point and hence the full cost-effectiveness cannot be assessed until sufficient time has passed for the intervention to demonstrate effect. To address this point, we clearly focused only on costs and benefits incurred within the financial year after the project was completed, i.e. on interventions that may have a high immediate impact on certain ecosystem services likely to be sensitive in the short term. While this approach partially solves the issue of ‘apportioning’, and also scales projects completed at different time points, we acknowledge that, especially in the case of peatlands, focusing only on the very short term implies overlooking longer term costs and benefits that are likely to arise as a result of the intervention. Therefore, to include some longer term considerations in the analysis, we additionally collected qualitative information about whether PA officers expected extra management efforts to be needed in the future to maintain the restoration benefits achieved as a result of the intervention. Because this information was a projection into the future, rather than an already observed effect, it could not be explicitly included in the cost-effectiveness ratios and could only be considered separately. This was also the case for other project merits (e.g. related to training and skills, extra working opportunities and capital/equipment availability resulting from the project implementation), which were not included in the calculations and could only be presented as qualitative (complementary) information. Future work should discuss ways of measuring and including also more ‘intangible’ benefits into the cost-effectiveness analysis. At this point, the information that cost-effectiveness ratios provide only gives a partial, short-term, picture.

In addition, when interpreting cost-effectiveness results, it is important to understand which factors might have driven the specific numbers obtained. In this sense, findings should ideally be weighted against aspects such as the type of peatland, its location and accessibility; the pre-restoration condition (and, related to that, the implementation of restoration efforts in the past); the specific technique employed; the time frame of the project; etc. Having a good amount of data available on restoration projects might have allowed us to perform regression analysis, to estimate statistically the variability of cost-effectiveness ratios depending on the above parameters. This may be possible in future years.

Despite all the limitations, policy-relevant information can be obtained starting from the cost-effectiveness analysis of peatland restoration. This is especially true where the ecological benefits of restoration are monetarised, through emission factors, into equivalent tons of CO_2 emissions sequestered, using the draft Tier 2 emission factors. If the analysis is done by restoration activity, information can be obtained on which restoration method is more cost-effective in reducing GHG emissions. Given the policy interest in reducing GHG to mitigate climate change, this approach to cost-effectiveness could be important to inform policy-makers regarding how to best achieve their emission targets and would also allow formal inclusion of the areas restored into the UK Greenhouse Gas Inventory. This also requires a standardised protocol to assess the area affected by restoration interventions. However, sometimes policy-makers do not know what the most appropriate targets are and they are interested in identifying them. In such case, cost-effectiveness analysis is not useful because it only evaluates the cheapest way of reaching a given target. It might then be worth considering the application of cost-benefit analysis (CBA), which compares the monetized benefits and costs of a given intervention and allows the gathering of information on the social desirability of different restoration efforts. Starting from some initial social cost and benefit curves, CBA can provide information about the socially-optimal level of restoration efforts that should be achieved to maximize social welfare. More work in this field is required in the future.

7. Recommendations

- The area restored by various interventions can be difficult to define. Some guidance should be produced to ensure a standard method is used to estimate the area affected by the restoration intervention
- A monitoring protocol of the immediate visual effects should be produced that allows a scale of effects to be incorporated. This would then allow future comparison of the effectiveness of different restoration projects. Visual perceptions of effectiveness may vary (some evidence was found in our surveys) and hence some visual guidance may be required.
- Cost aspects per unit area (length or area completed) for individual interventions were often not available. It should be assessed whether it should be asked that these costs be itemised on contractors' invoices as this would facilitate future cost:benefit assessments.
- Longer term (i.e. beyond one-year) costs and benefits should be assessed in future work, in order to gather evidence on the full cost effectiveness of peatland restoration.
- Monetarisation of the observed benefits should be considered for future work. For example, where information of pre- and post-ecological condition exists, effectiveness could be expressed in carbon abatement terms. This, combined with a robust methodology for estimating the areal extent of peatland restoration efforts, would allow formal inclusion of the net carbon abatement effect from peatland restoration in Scotland in the UK Greenhouse Gas Inventory, using the draft Tier 2 emission factors.

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Appendix 1. – Further material

Background on peatland restoration

Peatland restoration can take place on sites that are highly variable in starting conditions, due to the variety of factors that contributed to their degradation. For example, whilst many other European countries contain peatlands naturally harbouring trees, these were generally absent from the British Isles by the 1960s. In other European wooded peatlands, early results in the 1950s and 60s suggested increased timber productivity if the peat was drained. The drive to expand production forestry in the UK thus led to industrial scale drainage of open bogs in the 1960s onwards and subsequent planting with production timber species such as Sitka spruce and lodgepole pine. In other areas, drainage by Cuthbertson plough has been used since the turn of the 20th century to improve the grazing quality of the uplands, resulting in an estimated 28% of the Scottish peatlands showing signs of drainage (Artz et al., 2017; Aitkenhead et al., 2016). Drained sites in the lowland, due to the increased depth of oxygenation, can be prone to scrub invasion, which in turn may add to evapotranspiration losses and thereby enhance decomposition of the peat layers. Other degradation may have occurred either through historic deforestation over the previous centuries and subsequent erosion of exposed peat, in some cases combined with high grazing and trampling pressure, leading to large areas of exposed peat. These areas are prone to further degradation as the lack of a surface vegetation layer means that climatic influences (rain, wind, frost) can mobilise particulate peat or increase the decomposition of exposed peat by provision of air and radiative heating and thus lead to higher losses of gaseous carbon. The impact of peatland degradation on habitat quality, bird species of international concern and carbon emissions, was beginning to be realized by the early 1990s and started the beginning of peatland restoration efforts. Peatland restoration activities therefore differ depending on the starting conditions on the site, and in some cases, complex mixtures of interventions are required.

The overall aim of this project was to examine the costs and merits of the different practical techniques deployed to deliver peatland restoration projects in Scotland since 2010. Previous reviews either focused primarily on costs of the interventions (e.g. Chapman et al., 2012, Artz and McBride, 2017) or collated observed ecosystem service benefits or efficiencies of the interventions in a qualitative way, thus precluding formal cost-benefit or cost-efficiency analyses (e.g. Artz and McBride, 2017). Andersen et al (2016) reviewed the outcomes of EU-LIFE restoration projects between 1993 and 2015, which covered 80 projects across Europe, including some in the UK. They concluded that, while positive progress due to restoration activities could often be described for individual sites, comparative analyses were difficult due to a lack of a common set of scoring criteria to determine whether the target had been reached. In addition, many projects did not seem to state unambiguous targets for the project, and/or lacked monitoring, unrestored control sites or nearby locations that were in a reference state. Other authors have tried to put the cost of restoration into monetary context by examining the value that people place of improving the ecological condition of peatland (Martin-Ortega et al., 2017). A very recent study by Byg and Novo (2017) used interviews to gather qualitative data on the perceived effectiveness of the Peatland Action programme and found a number of ecosystem service benefits as well as general support for the effectiveness of the programme overall, but did not explore attributing these to particular interventions.

Project aim

We explored whether formal cost-effectiveness analysis (CEA) or cost: benefit analysis (CBA) can be applied to existing data, and provide a gap analysis. The project covered the following aspects:

i. Current state of the evidence underpinning different techniques for peatland restoration, covering academic and grey literature relevant to Scotland

ii. An analysis of costs of peatland restoration techniques for different rewetting applications, including capital and resource investment, and subsequent repair and maintenance costs, inclusive of labour cost.

iii. An analysis of the merits/benefits of different methods, including level of disturbance, durability of intervention, access, ground conditions.

iv. An analysis of the skills required to support different methods, and the extent to which specialist contractors or local labour are required. Is there evidence to indicate how costs might change in future as restoration becomes a more established practice?

8. Methods

Literature review

Evidence for the literature review was gathered using searches in Web of Science (academic), Googlescholar (academic/grey) and Google (grey) using Boolean searching of combinations of one out of each of the categories below combined with ‘AND’:

a) restoration, rewetting, drain blocking, ditch blocking, felling, erosion AND control, reprofiling, mulching, stump flipping, ground smoothing, bunding, trenching, tree harvesting, brash crushing, geojute, reseeding, revegetating, peat dam*, scrub AND control

b) (peat* OR fen OR bog OR mire)

c) cost, ecosystem service, benefit

Geographical restrictions were placed using the following term: 'AND (UK OR United Kingdom OR England OR Scotland OR Wales OR Ireland OR Brit*)'. The geographical scope focused on Scotland, although other evidence from the wider British Isles and selected evidence from Fennoscandia and Continental Europe was considered. Because of differing peatland types, damage types and climatic context (e.g. many peatlands in these regions are naturally wooded), evidence from outside of the UK was carefully vetted to ensure these fitted the peatland conditions and rewetting techniques likely to be encountered in Scotland. Evidence from tropical peatlands will generally not be relevant to Scotland and was excluded. Evidence from restoration undertaken before 2010 was generally excluded, except where it concerned techniques that are still used. Older evidence on techniques that have been discontinued due to ineffectiveness or lower cost-effectiveness, than current techniques were considered outside our scope. 'Grey literature' searches were performed on websites belonging to SNH, NE, FC, JNCC and their Irish equivalents. Thesis searching was done using British Library EThOS and DART-Europe E-theses. We also searched the Conservation Evidence website (https://www.conservationevidence.com/) and reviewed any papers related to peatland restoration effects that had been carried out in the UK or European countries with comparable climate (e.g. Germany, Poland, the Netherlands).

Table 1 in the main text lists the rewetting activity categories that were investigated. There are other interventions that are not rewetting and cannot always be assigned to have been intended to restore peatland, e.g. removal of grazing/trampling, cessation of burning, so we did not include these interventions in our study. At a minimum, cost and benefit data were considered for analysis at the top level of the primary rewetting activity, with more detailed analysis at the level of individual activities contributing to the rewetting activities dependent on available data volumes. Data were considered for analysis of differential costs and benefits for different peatland types (blanket bog, intermediate bog, lowland raised bog, fen) if available data volumes allowed.

Site selection for detailed surveys

Initial contact with SNH established that 150 restoration projects to date had been completed under Peatland Action funding (2012-March 2017). We did not consider projects started within the current financial year (2017-2018) as none had been completed at the time this project started. A further small number of potential restoration projects that had been carried out with other funding sources since 2010 were identified via contact with statutory agencies, the Peatland Code, and the IUCN Peatland Programme.

Details initially obtained for these projects included the primary restoration activity as per Table 1 as well as the centroid location for the site. The altitude for each site was confirmed in OS Mastermap. Distance to the nearest road was calculated in GoogleEarth by tracking the most likely (given the terrain and obstacles such as cliffs or water features), and shortest route to a metalled road. Distance from the metalled road to the nearest urban centre was calculated in GoogleMap Direction queries. These could potentially be automated but due to the relatively low number of observations it was deemed that this was quicker to do manually.

The resulting data on altitude, nearest urban centre and distance by road, together with a classifier for island locations, were combined and a weighted sample population for each primary restoration activity was identified for the online surveys by interrogating the relative distributions for each factor. This resulted in a reasonably representative sample population of 32 sites. The grant numbers for these sites were sent to the SNH Peatland Action team, who made introductions by email to the relevant persons who had received the grants as well as the relevant Peatland Action officers. If a confirmation was received that the individuals were willing to partake in the study in principle, an information email complete with consent form (Appendix 2) was sent. Information about the relevant contractor for each site was also requested by email to the recipients of grants, for whom the process was repeated.

If a signed consent form (or email confirming consent) was received, a survey token (unique number) was generated for that individual and the matched site. Access to the survey (see below) was via this token, thus negating the need to ask for personal details or site details within the survey. Only one researcher (RA1) had access to the personal information of respondents and restoration site names, grant numbers or location details. These data were further password-encrypted, with only RA1 having access to this password. All data are due to be destroyed after 2 months following the publication of this report.

Cost and benefit data collection – online survey

Some summary cost data and additionally some qualitative ecosystem service benefit data had been available to the project team through previous projects carried out for ClimateXChange (e.g. Artz and McBride, 2017). We did not have access to the costs for individual projects, however, and hence it was not feasible to use these data for cost-benefit or cost-efficiency analysis as we could not match observed benefits to costs. In addition, there were no quantitative data on benefits of the interventions available. SNH now require a full breakdown of costs for new applications (http://www.snh.gov.uk/climate-change/taking-action/carbon-management/peatland-action/information-for-applicants/). This information will be analysed by staff at SRUC/James Hutton Institute under a project funded by RESAS (RD1.1.4.). Due to the timelines of this project, however, we were not able to make use of the new data, as these will only become available after the application deadline (October 2017 onwards).

Therefore, following discussions with SNH, it was decided that new cost and benefit data needed to be collected in quantitative format for this project. We developed an online survey that asked detailed questions about the total project costs as well as specific costs (see below) that could be attributed to labour, capital and other costs (materials and fuel). We also asked questions about match funding, volunteer or other unpaid efforts, and if there had been any income foregone. To enable a quantitative analysis of the effectiveness or benefits of the interventions, we asked questions that respondents needed to put in context with their expectations prior to the work starting. This enables an analysis to be carried out on the achieved results as a proportion of the expected results. For example, we asked if the work had been completed as intended and asked respondents to scale their answers to 1 in the case of the work having been completed as planned, above 1 if e.g. a larger area was restored, and below 1 if less area was restored than planned. We also assessed the durability of the intervention (proportion of work lasting the year). This approach was also used to assess the achieved ecosystem service benefits, for which we only assessed a) alteration of the water table or surface wetness, b) changes in the amount of live vegetation cover , c) changes in the species complement (vegetation or other biota) , d) changes in the colour of runoff of water and e) aesthetic changes. Throughout the survey, we collected general information about the project and the peatland sites, including the restoration activity (or activities) being carried out, the pre- and post-restoration condition and the specific technique employed to carry out each activity. In terms of additional merits, were asked further questions on whether the project resulted in the creation of new skills and additional work opportunities, as well as in the availability of new (specialised) equipment/tools. For additional disbenefits we collected data on whether there had been unforeseen costs linked to access problems, disturbance, or repair work.

All questions were limited to ask respondents only to comment on their observations in the year following the project end, so that we could compare projects that had finished at different time points since 2012. This was done so as to not bias results towards restoration projects that had been completed earlier in time, as benefits might take time to accrue. However, we acknowledge that this approach does not allow for a full analysis of benefits achieved to date, so we also asked a question about potential longevity of the project and whether respondents perceived that additional efforts might be required on the sites to retain the restoration work results seen after 1 year. The majority of the questions could be skipped or ignored, and similarly, we allowed for detailed comments that might enable a more in-depth analysis of the factors involved in restoration success or failure. We aimed to gather data from Peatland Action officers (or people in similar functions at the statutory organisations or the Peatland Code team), the Grantees, and the Contractors. Not all questions were visible to all groups, for example, only Peatland Action officers were asked to describe the initial condition of the site in detail. This information allowed us to carry out a preliminary analysis of the likely carbon benefits. Similarly, only contractors were asked about their perceptions of changes in restoration costs over time. A copy of the survey can be requested from the main author of this report. The survey was constructed in LimeSurvey online software, which is hosted directly on the James Hutton server for enhanced data protection. Access to the survey was via unique numbers (tokens) only, as above, and no information was asked for within the survey that could identify an individual site or person. Completed surveys were downloaded on an ongoing basis, and data analysis could only identify individual projects by site number. The cost-effectiveness calculations were carried out by a single researcher (MR), who did not have access to the site or personal details of the respondents, thus anonymising the survey results. In cases where follow-up was required, MR identified the corresponding survey token, and RA1 identified the relevant person to contact. Telephone follow-ups were conducted by RA1 or RA2, without having reference to the other survey results to minimise introduction of bias.

We employed the above information to obtain cost-effectiveness per hectare or km. These were calculated as the 1) immediate cost-effectiveness (i.e.. the total costs for an intervention divided by the total area/length restored immediately after completion) and 2) 1-year cost-effectiveness (i.e. the total costs for an intervention divided by the total area/length restored immediately after completion multiplied by the effectiveness after 1 year)

Literature review results

The literature searches yielded a very large number of hits on two of the search engines (604 published since 2017 on GoogleScholar), 2,162 on ScienceDirect – 641 if limited to UK), due to the inability to filter by geographical region as most papers do not contain this information in the title or abstract. Hence, a large number of titles had to be scanned, the majority of which were excluded due to being either not relevant or containing no detail on restoration method, outcome or cost. In contrast, the filter on ISI Web of science was much more effective, with 430 publications identified in total. However, many of these were duplicated between different search term combinations, or found to be irrelevant upon skim reading of the abstract or whole paper (Appendix 2). A further 33 PhD theses were identified, of which 16 appeared to be relevant upon skim reading of the abstract (Appendix 2). Further information was retrieved using general internet searches with the same Boolean terms as well as a digest of the information included in the Conservation Evidence website.

Appendix 2. Consent form used for the surveys.

CONSENT FORM

Cost effectiveness of peatland restoration – ClimateXChange Scotland

I hereby consent that my name, my company's name and my written responses to survey questions be recorded, and similarly, that my responses to any follow-up telephone interview be audio recorded for the purpose of data collection during the duration of the ClimateXChange Scotland project.

I consent on the proviso that these will not be used in a manner that directly identifies me, my company, or the location and name of the restoration project I will be providing data for, and that the data will be destroyed within 2 months of the publication of the final project report.

I reserve the right to interrupt or quit the survey or interview at any time.

Name

Date

Signature

Appendix 3. Numbers of observations of different techniques used in individual survey returns.

token	**1**	**4**	**5**	**6**	**9**	**12**	**14**	**3**	**18**	**17**	**20**	**19**	**23**	**21**	**16**	**25**	**72**	**11**	**10**	**sum by technique**
normal age forestry harvesting	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	**1**
pre-commercial harvesting	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**2**
whole tree harvesting	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
felling to waste	1	0	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	**4**
whole tree mulching	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	**1**
ground smoothing/stump flipping	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
brashmat mulching	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
damming plough furrows	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
mulching ridges to fill furrows	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	**1**
brash crushing	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	**1**
cutting with chainsaws/clearing saws for regen	0	0	1	0	0	1	0	0	1	0	0	1	0	1	0	0	0	0	0	**5**
herbicide spraying/weedwiping	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	**2**
mulching/flailing/swiping	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	**1**
damming drains with peat	1	0	0	1	1	0	0	1	1	0	1	1	0	1	0	1	1	1	1	**13**
damming drains with timber	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
damming drains with plastic	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	1	0	1	**4**
damming drains with rocks	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
channel/stream damming to stop scouring	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	**1**
reprofiling drains/grips	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	**1**
hand pulling regen	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	**1**
surface low bunding	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	**2**
spreading heather brush as a surface mulch	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
geojute bare peat covering	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	**1**
revegetating by spreading cut veg.	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	**2**
native bog woodland creation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
bunding to create smaller parcels of land	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**1**
reprofiling hags/peat banks	0	1	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	**3**
sum by project	**3**	**4**	**3**	**2**	**2**	**4**	**0**	**1**	**3**	**2**	**2**	**4**	**3**	**2**	**1**	**1**	**3**	**3**	**3**	

Appendix 4. Literature search results. Search engines used: 1- ISI web of Knowledge; 2 – Googlescholar; 3 - British Library EThOS

Search terms (*search terms in bold in line one repeated in following lines)	Initially identified	Retained on the basis of title and abstract (additional only after first line)	Further exclusions after scanning the full paper (given only for full list)	Search engine
Restoration AND **(peat* OR fen OR bog OR mire) AND (UK OR United Kingdom OR England OR Scotland OR Wales OR Ireland OR Brit*)**	176 33	67 16	40 5	1,2 3
Rewetting AND *	33	4		1,2
Drain blocking AND *	43	1		1,2
Ditch blocking AND *	22	2		1,2
Felling AND *	69	2		1,2
Erosion AND control AND *	53	3		1,2
Reprofiling AND *	1	0		1,2
Mulching AND *	1	0		1,2
Stump flipping AND*	0	0		1,2
Ground smoothing AND *	1	0		1,2
Bunding AND *	0	0		1,2
Trenching AND *	0	0		1,2
Tree harvesting AND *	19	2		1,2
Brash crushing AND *	0	0		1,2
Geojute AND *	0	0		1,2
Reseeding AND *	6	1		1,2
Revegetating AND *	1	0		1,2
Peat dam* AND *	16	1		1,2
Scrub AND control AND *	5	0		1,2
Total remaining	463	99	70	

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