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Review

New approaches to the restoration of shallow marginal peatlands

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ABSTRACT

Globally, the historic and recent exploitation of peatlands through management practices such as agricultural reclamation, peat harvesting or forestry, have caused extensive damage to these ecosystems. Their value is now increasingly recognised, and restoration and rehabilitation programmes are underway to improve some of the ecosystem services provided by peatlands: blocking drainage ditches in deep peat has been shown to improve the storage of water, decrease carbon losses in the long-term, and improve biodiversity. However, whilst the restoration process has benefitted from experience and technical advice gained from restoration of deep peatlands, shallow peatlands have received less attention in the literature, despite being extensive in both uplands and lowlands. Using the experience gained from the restoration of the shallow peatlands of Exmoor National Park (UK), and two test catchments in particular, this paper provides technical guidance which can be applied to the restoration of other shallow peatlands worldwide. Experience showed that integrating knowledge of the historical environment at the planning stage of restoration was essential, as it enabled the effective mitigation of any threat to archaeological features and sites. The use of bales, commonly employed in other upland ecosystems, was found to be problematic. Instead, 'leaky dams' or wood and peat combination dams were used, which are both more efficient at reducing and diverting the flow, and longer lasting than bale dams. Finally, an average restoration cost (£306 ha^{-1}) for Exmoor, below the median national value across the whole of the UK, demonstrates the cost-effectiveness of these techniques. However, local differences in peat depth and ditch characteristics (i.e. length, depth and width) between sites affect both the feasibility and the cost of restoration. Overall, the restoration of shallow peatlands is shown to be technically viable; this paper provides a template for such process over analogous landscapes.

1. Introduction

Peatlands are mostly found in areas of high precipitation excess and poor drainage in the temperate, boreal and coastal regions of the world (Holden et al., 2004; Page et al., 2009), and contain between a third and a half of the global soil carbon (C) store (Holden, 2005). For a long time, peatlands have been solely considered for their ability to provide society with raw materials or energy. Whilst their domestic use for fuel probably began several thousands of years ago (Chapman et al., 2003), peatlands are now intensely used for fuel in industry and for agricultural purposes (Oleszczuk et al., 2008; Holmgren et al., 2008), with large detrimental consequences on C storage, hydrology and biodiversity. Today the extent of peatlands, worldwide, is uncertain due to the general lack of comparable data available and differences in the definition criteria (Joosten and Clarke, 2002). In 2002, it was estimated that 16% of the area covered by peatlands globally had been degraded by human activity and lost (Joosten and Clarke, 2002). According to Chapman et al. (2003), of the active peatland converted to other uses in non-tropical areas, 50% were lost to

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agriculture, 30% to forestry, 10% to peat extraction (i.e. fuel and horticulture), and the remainder to urbanisation, erosion, water reservoirs and other usages. Peat extraction on industrial scales has mostly affected Ireland, Central Europe and North America, whereas in other countries, such as the UK, damage to peatlands originates from both historical practices (e.g. burning, grazing, peat cutting for fuel at small scales and for domestic use) and contemporary exploitation (e.g. drainage for forestry, commercial extraction for horticulture and agricultural reclamation). Peatlands in the tropics are also subjected to human-induced damage. In 2007, it was estimated that 60% of Indonesian and Malaysian peat swamps had been converted for agricultural use, pulpwood and palm oil plantations (Miettinen and Liew, 2010), with vast areas within intact peatland complexes in the tropics being degraded by the introduction of wide canals and drainage channels for expediting peat and wood extraction (Jaenicke et al., 2010).

All peatland conversion and exploitation starts with drainage, which drastically affects the hydrological function of the peat, leading to drier soils, flashier flow regimes, and increased flood risk downstream (Holden et al., 2004). In turn, drainage can cause large C losses through both gaseous and fluvial pathways (e.g. Waddington et al., 2008; Joosten, 2010; Moore et al., 2013), and is generally accepted to have negative effects on ecological diversity (specifically, loss of *Sphagnum* spp. coverage in the northern hemisphere; Jauhiainen et al., 2002; Mälson et al., 2008). Research efforts to study these damaging consequences have also shed light on the wider range of ecosystem services (ES) provided by peatlands, which were previously largely overlooked (e.g. the supply of drinking water, their recreational or cultural value; Joosten and Clarke, 2002), and broadly points towards the need for a more holistic restoration and management strategy of these environments (Bonn et al., 2010; Holden et al., 2007).

Recently, increased concerns relating to the global decline in peatlands and increased C emissions due to climate change have led to a rise in peatland conservation directives and guidelines worldwide (e.g. Bragg and Lindsay, 2003; Quinty and Rochefort, 2003). In the UK, a range of conservation or management programmes aiming to restore peatlands to a 'functioning' condition (i.e. peat accumulating mires) have stemmed from the recognition of the degradation of peatland by bodies such as the IUCN (Bain et al., 2011), and their protection under the EU Habitats Council Directive (1992). The wide range of ES that are now simultaneously addressed by complex restoration programs have also increased the awareness and involvement of a range of stakeholders and/or customers benefiting from them, who are now willing to fund restoration. These include public authorities (e.g. national parks), but also private bodies, such as water utilities, land owners or peat extraction companies.

There is no general agreement on the exact definition of peat, and furthermore, on how to differentiate deep and shallow peat soils. In the present study, the term "shallow peat" designates peaty soils that range between 10 cm and 1 m, as defined by JNCC (2011). Shallow peat soils are found throughout the world (e.g. Canada, Eastern Europe, Russia or Indonesia), usually on the margins of deeper peat reserves (i.e. Jaenicke et al., 2008; JNCC, 2011; Vompersky et al., 2011). However, extensive literature review has highlighted that information on the restoration of shallow peatlands remains sparse, as efforts tend to be concentrated on deeper peat reserves. In the UK, shallow peatlands are particularly well represented, covering nearly 60% of the total extent of peatlands in the country (JNCC, 2011), and are especially found on the south west margins of peatland distribution (e.g. Brecon Beacons in South Wales, Exmoor and Bodmin Moor in England).

In the UK, restoration schemes are underway on both shallow and deep peat (Holden et al., 2008). Worldwide, however, both the process of restoration and research on its consequences has mostly focused on deep peat (e.g. Armstrong et al., 2009; Rochefort and Quinty, 2003). Shallow peatlands are often overlooked when restoration projects are considered, even though they may provide a suite of important ES (Grand-Clement et al., 2013). Moreover, due to their marginal locations, these peatlands are likely to be more sensitive to human intervention (e.g. through drainage for agricultural reclamation) and climate change, as the impact of future climate change predictions on marginal peatlands may rapidly lead to conditions where shallow peats can no longer support peat formation (Gallego-Sala et al., 2010). Hence, these areas of shallow peatlands need to be considered when restoration projects are planned - even if it may only be possible to limit the damage of existing management practices and prevent the disappearance of the remaining stock, rather than promote active growth of peat and accumulation of carbon.

The aim of this paper is to evaluate the range of approaches available for restoration of shallow peatlands. Restoration techniques employed worldwide, and in the UK in particular, are discussed to explore the relevance of existing techniques for shallow peat landscapes, and to demonstrate how restoration schemes in such ecosystems may need to be engineered differently (Section 2). Using the case study of Exmoor National Park (UK), a practical and step-by-step guidance for the restoration of shallow peatlands is provided (Section 3), based both on the methods usually employed in deep peat, and on lessons learnt by the Exmoor Mires Project. Preliminary results from the restoration of two test catchments are presented in Section 4. Finally, Section 5 provides some discussion points and conclusions on the technical and financial feasibility of such processes, in order to understand how these extensive peatlands may be managed in a more resilient manner in the future, and how these techniques can be employed in other similar environments.

2. Peatland restoration throughout the world: an overview

2.1. Technical aspects: same objectives, different problems and methods

Most land management interventions in peatlands require drainage of the soil. However, the damage caused by each practice varies greatly. For instance, regular drainage ditches cut in a blanket mire will cause localised breaks in the surface, whereas commercial extraction of peat removes the entire top layer, potentially going below the acrotelm. This creates an artificial topography which might remain bare or covered by different plant communities reflecting past extraction methods (Poulin et al., 2005). As a result, detrimental consequences of peat cutting usually go beyond the direct drying out of the peat. Blocking drainage ditches is the most common restoration solution, and is usually implemented to restore peatlands to something resembling a more 'normal' hydrological function. Ditch blocking can increase the water table depth and reduce concentrated and/or overland flow (Wilson et al., 2010). Practically, blocks will only affect a limited area immediately upstream; efficiency is achieved by placing a number of blocks at regular intervals along the ditch system (Trotter et al., 2005). There are two main types of dams that will meet two different objectives:

- *Impermeable* dams (i) allow the formation of a low-energy pool of water immediately upstream from the block, which has, in northern peatlands, the potential to encourage the development of aquatic *Sphagnum* spp. carpets along the line of the ditch itself (Lindsay, 2010); (ii) elevate the level of water upslope from the dam and in adjacent areas of peat, and induce re-wetting, thereby creating conditions suited to *Sphagnum* moss regrowth (Lindsay, 2010); (iii) shed water from the ditch as overland flow down and across slope into previously dry areas (Smith, 2010).

- *Permeable* dams are low-efficiency water barriers used to decrease flow velocities. They will trap sediment and allow the ditch to fill, therefore minimising erosion (Holden et al., 2004; Lindsay, 2010) and promoting the progressive vegetation recolonisation over time.

Worldwide, peat exploitation has mainly been undertaken in deep peat. Restoration efforts are therefore concentrated in these environments, and there is currently little evidence of restoration in shallow peatlands. The blocking of drainage features is however used throughout the world in restoration programs regardless of peat depth, either solely or in conjunction with other measures (i.e. re-vegetation or removal of trees), as summarised in Table 1. This table is not exhaustive, but illustrates the general approaches to restoration across different land uses globally. Depending on locations, impermeable blocks are usually made of wood, peat or plastic piling). In the tropics, large dams can be made of compacted peat within a wooden structure (Ritzema et al., 2014). In the Tibetan plateau, other blocking techniques have been tested (i.e. sandbags, concrete and stones), with mixed success (Zhang et al., 2012). In the UK, permeable dams are typically constructed by placing bales of local vegetation in the channel (e.g. *Calluna vulgaris* in the north of England, *Molinia caerulea* in the south west of England, or brash made from local conifer clearances in Wales).

In areas that have been subject to large scale peat exploitation (e.g. North America or Ireland), the acrotelm of the peat has been totally removed, leaving large areas of bare peat exposed (Quinty and Rochefort, 2003). The main purpose of restoration then becomes to reintroduce C accumulating vegetation by spreading *Sphagnum* spp. from a donor site before fertilisation (Rochefort et al., 2003). This method of restoration only uses the blocking of the drainage ditches as a final step because rewetting would otherwise prevent access by heavy machinery. Some natural revegetation of cutover peatlands has been observed after sites have been abandoned for several years, mostly after traditional block cutting methods were used (e.g. Robert et al., 1999); in those cases, blocking of the drainage ditches remains the method of choice (González et al., 2014). Revegetation is also used in the UK to address bare peat problems, mostly due to erosion and pollution (e.g. Lunt et al., 2010).

In the tropics, large volumes of water have to leave both pristine and damaged peat domes (Dommain et al., 2010). Restoration efforts therefore focus on both slowing down flow and dispersing the water across the dome, and retaining water for longer periods during the dry season (Jaenicke et al., 2010). Permeable dams aim to maintain high water levels that will eventually lead to sedimentation (Ritzema et al., 2014), but need to be adapted to the low load bearing capacity (Salmah, 1992) and high hydraulic conductivity of tropical peat (Wösten and Ritzema, 2001). In the case of large canals, wooden structures of local wood (e.g. gallam wood) are filled with compressed peat (Ritzema et al., 2014), whilst smaller canals are blocked using low cost local material (Page et al., 2009). In time, these dams help with re-establishment of the vegetation, slope stabilisation and reduce erosion; however, they have a limited lifetime, and will eventually disintegrate (Ritzema et al., 2014). Moreover, natural regeneration of the vegetation might not be possible when the peat swamp ecosystem has entered a

Table 1
Restoration aims and measures to address several types of peatland damage globally; NI indicates area with no information.

Land use	Type of peatlands	Technique of damage	Restoration aims	Restoration technique	Prevalent location	Reference
Commercial peat cutting	Lowlands fens, Ombrotrophic bogs	Milling and vacuum harvest	Restore vegetation (*Sphagnum* spp.) on bare peat and C accumulation	Spread of *Sphagnum* spp. from a nearby donor site protected by straw mulch, ditch blocking, phosphorus fertilization.	Canada, Ireland, Eastern Europe	Rochefort et al. (2003) Andersen et al. (2010) Lucchese et al. (2010) Triisberg et al. (2011)
		"Sausage cutting" Block cut harvest	Restore water table levels	Inundation of site, ditch blocking.	Canada, Ireland, UK, Germany, The Netherlands,	Robert et al. (1999) Tomassen et al. (2010) Bönsel and Sonneck (2011) González et al. (2014)
Domestic hand cutting	Lowlands/uplands ombrotrophic bogs	Block cut harvest	Increase of water table levels	Blocks	UK, Ireland	NI
Forestry	Ombrotrophic bogs	Drainage and tree planting	Restoration of the original species composition and function of the ecosystem	Removal of trees; damming and filling of ditches; no seeding/ planting required	Scandinavia, Eastern Europe, UK	Vasander et al. (2003)
	Lowland fens		Restore water table levels, scrub clearance			Haapahleto et al. (2010)
Agriculture reclamation/ food production/ logging	Ombrotrophic bogs/mires	Regular drains/ grazing	Reestablishment of hydrological function/vegetation and C accumulation	Ditch blocking, revegetation of bare peat	UK, Germany	Wallage et al. (2006) Armstrong et al. (2009) Parry et al. (2014)
	Lowland fens	Drainage ditches	Restore the hydrological behaviour and vegetation	Ditch blocking	UK, The Netherlands, Germany	Komulainen et al. (1999)
	Highland marsh			Ditch blocking, revegetation of bare peat	China	Zhang et al. (2012)
	Tropical peat swamps forests	Large drains/canals dug (up to 25 m wide)	Re-establishing buttress vegetation to improve hydraulic sub-structure	Large scale canal blocking to reduce water drawdown	South East Asia	Ritzema et al. (2014) Jauhiainen et al. (2008) Dommian et al. (2010)

retrogressive state, due for instance to low dry season water levels and wet season flooding, low nutrient supply, low seed dispersal, or competition with herbaceous vegetation (Page et al., 2009). Reseeding is currently being trialled, but higher water table levels still show little impact on seedling survival (Page et al., 2009).

2.2. Recognition of the need for restoration

There is a growing body of evidence showing that restoration of hydrological function in damaged peatlands, worldwide, can improve a suite of ES, such as carbon storage, the provision of water or the support of biodiversity, both on-site and downstream. Table 2 summarises these effects and highlights the general research focus on deep peat, due to their wider exploitation and subsequent restoration, whereas little is currently known about the changes occurring in shallow peatlands. Overall, the extent to which hydrological and ecological change can actually be achieved remains unknown. The condition of the peat (e.g. structure and compaction) is depending on the type and degree of damage, how long ago it occurred (e.g. the past decade or century), and overlapping practices (e.g. burning or grazing). This makes restoration of heavily damaged sites complex, slow to recover, and very costly. This is especially the case for sites where the acrotelm has been removed or where complex re-vegetation techniques of bare peat are employed. Studies focusing on long-term improvements (i.e. over 10 years) have shown many positive changes (e.g. Haapalehto et al., 2010; González and Rochefort, 2014; Strack and Zuback, 2013). However, even after that time, most sites tend to reach an assemblage of vegetation communities only resembling that of pristine peatlands (Haapalehto et al., 2010; Strack and Zuback, 2013). The extent of the damage should therefore be considered during the establishment of the restoration objectives; such factors also highlight the need for a holistic approach to evaluate the success of restoration, at both small and large spatial and temporal scales.

2.3. Restoration programs in the UK: the importance of shallow peatlands

In the UK, figures by The Peat Compendium (2014) indicate that there are currently 29 upland and 51 lowland peatland restoration projects (Fig. 1), covering a range of shallow and deep peatland types, from blanket bog to heathland, raised bogs and fen/marsh/swamp ecosystems. Most projects focus on restoring ecological and hydrological functions, or whole ecosystem functions; in many cases, biodiversity and hydrological restoration are key aims. These goals should therefore need to be considered both in the planning of the restoration and in the choice of techniques to use.

Several studies have implemented restoration techniques in deep peat (i.e. Armstrong et al., 2009; O'Brien et al., 2007; Parry et al., 2014; Schumann and Joosten, 2008; The Yorkshire Peat Partnership, 2012a, 2012b), but shallow peatlands are rarely mentioned. The key question is therefore whether the techniques developed in deep peat can be used in other peatlands, where damage is different, but also where the benefits of restoration may be diverse. Projects working on shallow peatlands have often called upon past experience from deep peatlands in order to develop their own restoration approaches. For instance, the range of techniques employed for re-vegetation and gully blocking have been proven successful in many cases in reducing deep peatland erosion (e.g. Trotter et al., 2005), and could, in theory, be applied to shallow peatland. However, these environments rarely erode via similar processes to deep peat (i.e. gully formation) and bare peat areas are rare. Instead, shallow peatlands may lose C quite subtly, via both fluvial (dissolved and particulate organic C) and gaseous (CO_2) pathways, so it is unlikely that techniques developed to combat erosion of deep or bare peat will be appropriate. Instead, the main benefit of the restoration of shallow and heavily drained peatlands may be to enhance water storage, further leading to other benefits (i.e. increase water quality and biodiversity, lower CO_2 emissions).

It is also likely that the lack of research conducted on shallow peatlands relates to a common assumption that they are of lower significance, due to their smaller C reserves. However, shallow blanket peatlands may have already been damaged (by overcutting and/or drainage) which reduced their functional depth and made them more vulnerable to land management and climate change. As such, we argue that shallow and climatically marginal peatlands might actually be more at risk of disappearance than deeper peatlands, and may therefore be more important to target within conservation objectives. Such a view is supported by the work of Gallego-Sala et al. (2010) and Clark et al. (2010) who showed that the shallow peatlands of Exmoor, which are located at the southern limit of blanket bogs in the UK, might lie outside of their bioclimatic envelope as soon as 2050, thereby limiting peat formation. In this case, land management is likely to be an additional factor, increasing the drying of the peat. Restoration must consequently support both the conservation of existing peat, but also the formation of peat in the future, where climate allows. Given the lack of official guidelines on restoration techniques in shallow peatlands worldwide, the present review of techniques specifically designed for these environments will be beneficial for future projects.

3. The restoration of shallow marginal peatlands: planning and decision making in Exmoor National Park

3.1. Restoration planning: the establishment of the restoration plans

The moorlands of Exmoor National Park contain a significant amount of blanket bog (mostly shallow) and valley mires (Giddens et al., 1996). These typically shallow peats have been drained, primarily for agricultural intensification during the 19th and 20th centuries, but have also been affected by domestic hand cutting for fuel since at least medieval times. Consequently, these peatlands have dried out and are highly degraded. The impact on the vegetation composition is visible through the presence *Molinia caerulea* (Purple Moor Grass), with very little *Sphagnum* spp. normally found in 'pristine' blanket bogs. The case for restoration of shallow peatlands is therefore strong, but the scientific evidence proving the benefit of such work in these environments is currently lacking. The Exmoor Mires Project has been working to restore 1019 ha of damaged peatlands since 2010 by blocking drainage ditches; the methodology developed over time is outlined in this section.

The first stage in the restoration of degraded peatlands is the assessment of both the extent and nature of the damage before establishing restoration plans. Decisions are made depending on the existing condition of the peat, the purpose of the restoration, and the impact of interventions on the surrounding landscape. The steps proposed for restoration planning on shallow peat by ditch blocking are detailed in Fig. 2. This guide builds upon the list of considerations proposed by Adamson and Gardner (2004), which include: (1) current and past management of the area; (2) flora and fauna; (3) local information; (4) additional considerations (e.g. legal and statutory obligations). Further to these, the Exmoor Mires Project also considers the Historic Environment (HE), public access, availability and type of funding, and the various uses of the landscape by a wide range of stakeholders, including farmers and land owners.

A key element of the decision making process on Exmoor (Fig. 2) relates to the depth of the peat and the existence of the damage, as interventions might expose bare peat or underlying mineral soil,

Table 2
Summary of the observed effects of restoration on selected ES, in the field and at various time scales, after anthropogenic use of peatlands; NI refers to no information stated, DWT stands for depth to water table, and ** indicates results that are non-statistically significant.

Ecosystem service	Process quantified	Effect	Context	Cause of damage	Location	Peat depth (m)	Timescale post restoration	Reference
C storage	CO_2	Decreased CO_2 emission	Bog	Industrial cutaway peat	Ireland	0.5	6–9 years	Wilson et al. (2013)
					Canada	NI	10 years	Strack and Zuback (2013)
					Finland	1	10 years	Soini et al. (2010)
			Raised bog	Peat harvesting	Finland	1	3 years	Tuitilla et al. (1999)
			Minerotrophic fen, ombrotrophic bog	Forestry	Finland	NI	2 years	Komulainen et al. (1999)
		No significant difference	Tropical swamp forest	Drainage for logging; Drainage and burning	Indonesia	4.4 to 7.8 (mean)	12 months	Page et al. (2009) Jauhiainen et al. (2008)
		Increased CO_2 from decomposition of straw mulch applied	Bog	Industrial cutaway peat	Canada	NI	1 year	Petrone et al. (2001)
	CH_4	Increased CH_4 with wetter conditions, w/o *Sphagnum* spp., *Eriophorum* spp. and *Juncus* spp cover and primary production	Raised bog	Industrial cutaway peat	Canada	1.5–1.6 (mean)	3 years	Waddington and Day (2007)
			Bog	Industrial cutaway peat	Canada	NI	10 years	Strack and Zuback (2013)
			Raised bog	Peat harvesting	Finland	1	3 years	Tuittila et al. (2000)
			Atlantic blanket bog	Industrial milled peat harvesting	Ireland	0.5 remaining	7–9 years	Wilson et al. (2013)
			Fen			Up to 1.8	10 years	Wilson et al. (2009)
			Minerotrophic fen, ombrotrophic bog	Forestry	Finland	NI	2 years	Kommulainen et al. (1998)
			Blanket bog	Drainage	UK	2	1–3 years	Cooper et al. (2014)
		No change	Tropical swamp forest	Drainage with/without burning, and logging	Indonesia	4.4 to 7.8 (mean)	12 months	Page et al. (2009)**
		Weak CH_4 sink; no waterlogged conditions					2 years	Jauhiainen et al. (2008)
	N_2O	Decreased N_2O emissions	Bog	Drained/cut	Germany	NI	6 months/ 10 years	Drösler (2005)
		Negligible flux	Atlantic blanket bog	Industrial milled peat harvesting	Ireland	0.5 remaining	7–9 yrs	Wilson et al. (2013)
	Gas balance	C sink on vegetated plots	Atlantic blanket bog	Industrial milled peat harvesting	Ireland	0.5 remaining	7–9 yrs	Wilson et al. (2013)
		C source on rewetted bare peat						
C storage/ water quality	DOC losses and colour	Increased DOC concentrations	Blanket peat	Drainage	UK	NI	10 months	Worrall et al. (2007)
						Deep	Up to 1 year	Jonczyk et al. (2009)**
						NI	3 years	Wilson et al. (2011)
		Increased DOC conc./ increased DOC export	Bog	Industrial cutaway peat	Canada	NI	3 years	Waddington et al. (2008)
		Increased DOC conc./ decreased DOC export	Upland peat	Drainage	UK	Deep	2 years	Gibson et al. (2009)
						NI	Up to 3 years	O'Brien et al. (2008)
		Decreased DOC concentration	Upland peat	Drainage	UK	Up to 1.5	1 year	Turner et al. (2013)
						Over 2	6 years	Wallage et al. (2006)
						2	7 years	Armstrong et al. (2010)
			Fen	Peat extraction	Germany	~6	20 years	Höll et al. (2009)
			Bog	Industrial cutaway peat	Canada	NI	10 years	Strack et al. (2015)
		Decreased DOC conc./ decreased DOC export	Bog	Industrial cutaway peat	Canada	NI	10 years	Strack and Zuback (2013)

(*continued on next page*)

Table 2 (*continued*)

Ecosystem service	Process quantified	Effect	Context	Cause of damage	Location	Peat depth (m)	Timescale post restoration	Reference
Water provision	Water table depth	Increase in DWT	Blanket peat	Drained	UK	NI	10 months	Worrall et al. (2007)
							Up to 1 year	Jonczyk et al. (2009)
							Up to 2.5 years	O'Brien et al. (2008)
				Drained and cut	UK	NI	Up to 2 years	Wilson et al. (2010)
			High altitude peat	Drained and cut	China	NI	2 years	Zhang et al. (2012)
			Minerotrophic fen, ombrotrophic bog	Forestry	Finland	NI	2 years	Komulainen et al. (1999)
							3 years	Jauhiainen et al. (2002)
							1 to 3; 10 years	Haapalehto et al. (2010)
			Ombrotrophic peat	Cutaway peat (not revegetated)	Canada	1.5–3	3 years	Shantz and Price (2006b)
						NI	2 years	Shantz and Price (2006a)
		Increased annual minimum DWT, higher mean DWT	Tropical peat swamp forest	Drainage and logging	Indonesia	4.4–7.8 (mean)	12 months	Page et al. (2009)
	Runoff	Reduced and/or slower runoff	Blanket peat	Drained	UK	NI	17 months	Jonczyk et al. (2009)
							Up to 3 years	Wilson et al. (2010)
			Ombrotrophic peat	Cutaway peat (not revegetated)	Canada	1.5–3	3 years	Shantz and Price (2006b)
						NI	2 years	Shantz and Price (2006a)
		Greater and faster peak from wetter antecedent conditions	Ombrotrophic peat	Cutaway peat (not revegetated)	Canada	1.5–3	3 years	Shantz and Price (2006b)
		Less flashy peaks, buffered system	Blanket peat	Drained and cut	UK	NI	Up to 2 years	Wilson et al. (2011)
	Lag	Increased lag	Blanket peat	Drained	UK	NI	Up to 3 years	Wilson et al. (2010)
	Pools	Flooding behind bunds during snowmelt	Ombrotrophic peat	Cutaway peat (not revegetated)	Canada	NI	2 years	Shantz and Price (2006a)
Biodiversity	Vegetation communities	Natural recolonisation of *Eriophorum* spp. and/or *Sphagnum* spp.	Blanket bog	Drainage features from erosion	UK	NI	1 year	Evans et al. (2005)
			Atlantic Blanket Bog	Drainage	UK	NI	18 months	Peacock et al. (2013)
			Blanket Bog				11 years	Bellamy et al. (2012)
			Minerotrophic fen, ombrotrophic bog	Forestry	Finland	NI	2 years	Komulainen et al. (1999)
							3 years	Jauhiainen et al. (2002)
							Up to 3; 10 years	Haapalehto et al. (2010)
			Raised bog	Peat cutting	UK	NI	1–6 years	Mawby (1995)
				Industrial cutaway peat	Canada	1.5–1.6 (mean)	3 years	Waddington and Day (2007)
			Atlantic bog	Cutaway peat	Ireland	0.5 to 1	2 years	Farrell and Doyle (2003)
		No significant change	Minerotrophic fen, ombrotrophic bog	Forestry	Czech Republic	NI	12 months	Urbanova et al. (2012)
		Little short-term effect of revegetation and blocking on survival of seedling	Tropical swamp forest	Drainage for logging	Indonesia	4.4–7.8 (mean)	12 months	Page et al. (2009)
		Recolonisation of local wetland species	High altitude peat	Drainage and peat cutting	China	NI	2 years	Zhang et al. (2012)

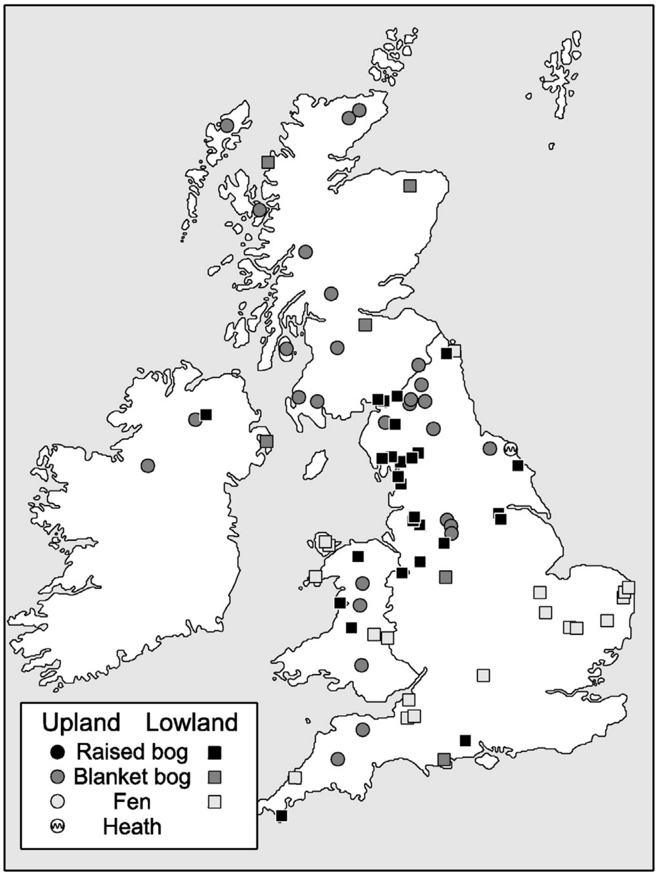

Fig. 1. Location and types of peatland restoration projects in the UK (based on data from The Peat Compendium, 2014).

and thus promote erosion. On land used for livestock grazing, the potential impact of restoration has to be considered on both the zone in question and the surrounding area: restoration likely to prevent or change the appropriate management practices in the vicinity (i.e. conservation grazing or regular cutting and baling of *Molinia caerulea*) should not be carried out, as this can have a financial impact for farmers for agricultural productivity and the payment of single-farm payments under agri-environment schemes (e.g. the Higher Level Stewardship scheme; Natural England, 2012) which dictates the grazing density. However, other statutory regulations (i.e. conservation status) might mean that restoration has to be carried out to meet certain regulations. Restoration might also be compromised if it prevents public right of way or the usage of a main track for land managers. The presence of sensitive species, i.e. European Protected Species (The Conservation of Habitats and Species Regulations, 2010), can prevent restoration at certain time of year, but rarely halt restoration completely. In practice, surveys should be undertaken to identify the presence of birds, reptiles, amphibians or any European protected species. In some cases, building blocks by hand could be considered a less damaging alternative to heavy machinery. Finally, areas of archaeological significances should be considered and potentially avoided.

3.2. Choice of techniques for ditch blocking

Once the ditches have been selected, decisions have to be made on which technique to employ. A decision tree (Fig. 3) details all possible restoration techniques available (although not all were employed on Exmoor). Each corresponding technique is illustrated in Fig. 4, whilst Supplementary material Table 1 details their specific technical characteristics.

According to Armstrong et al. (2009), none of the techniques employed throughout the UK were worse or better than others in

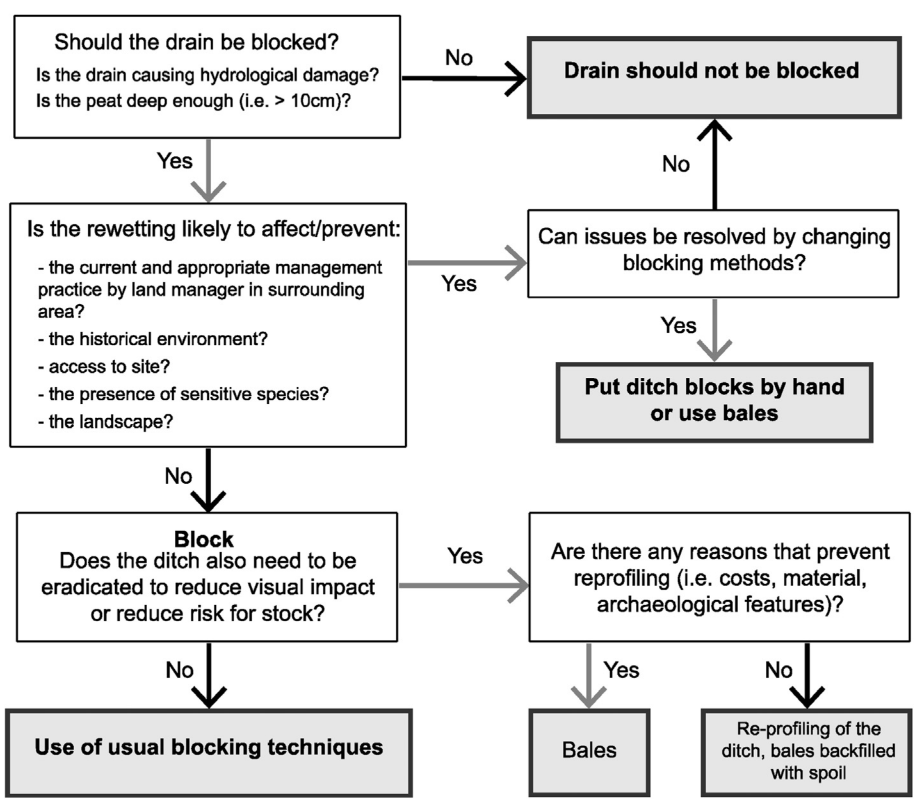

Fig. 2. Guide for the choice of ditch to be blocked during the preparation of restoration plans.

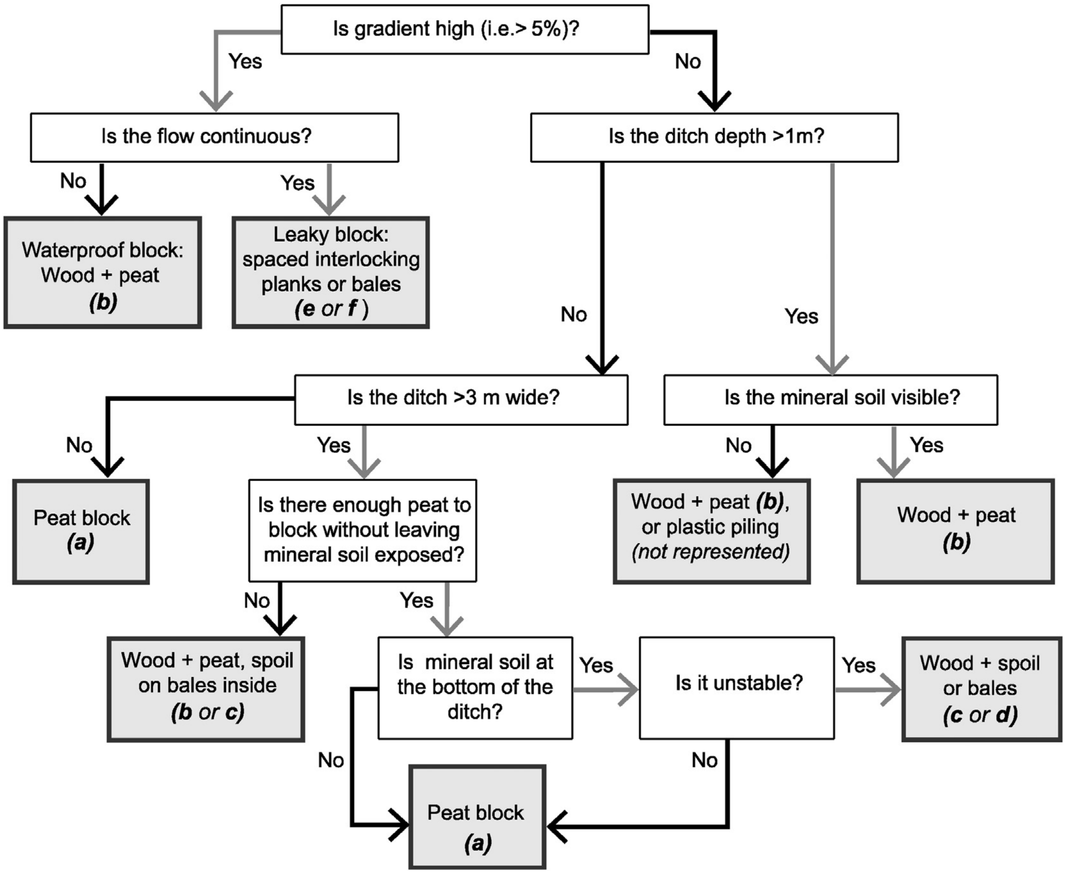

Fig. 3. Ditch blocking decision tree for the restoration of shallow peatlands (letters in bracket refer to matching drawings in Fig. 4; slope and ditch dimensions are based on the damaged found on and may vary elsewhere).

restoring the water storage capacity of the peatland. However, experience on Exmoor showed that some may be better suited and more effective on shallow peatlands than others. The choice has to be made on a case-by-case basis, considering the specifics of each block type, the aims of restoration, the costs and budget, the technology available or the accessibility of the site. Local conditions, including peat depth, ditch size, slope gradient, vegetation or erosion status are all key factors which influence the type of block selected, as discussed below.

The gradient will partly impact on the type of flow (i.e. continuous or intermittent): steep slopes (i.e. over 5%) are more likely to be affected by erosion and therefore may require substantial restoration measures. In the case of concentrated flowpaths (i.e. drainage ditches or gullies), permeable, or "leaky", dams (i.e. wood with bales or peat, Fig. 4c or f) will help to slow the flow of water, whereas impermeable dams would fill very quickly, overspill, or might become instable and burst (O'Brien et al., 2007). Spaced wooden blocks covered with peat (Fig. 4f) provide an efficient alternative to bales, as they act as impermeable dam at low flow, but behave as permeable dams and let water overtop at high flow. On steep gradients, impermeable dams with supporting stakes are effective in situations of non-continuous flows, as long as the peat is deep enough to support the wood. On Exmoor, bales used for leaky dams are made out of the local vegetation (i.e. *Molinia caerulea*). They can also be placed in the spill area to reduce the depth of the pool, the energy of the flow and prevent erosion via headcutting, or around the dam to cover bare ground and encourage re-seeding. However, the process of baling (i.e. machinery required on site potentially leading to soil compaction) and the need for long periods of dry weather for site access, make these approaches costly and unpractical.

Although they can hold large amounts of water, plastic piling dams are not suitable for shallow peatlands, due to the high risk of leaking if inserted in mineral soils. The visual impact of the technique also made this a more applicable approach for deep peat, particularly in conditions of slopes under 5%, in large ditches with a cross section of over 0.7 m^2 (Armstrong et al., 2009; Brooks and Stoneman, 1997), or in gullies of 2–3 m width by 1–1.5 m depth (O'Brien et al., 2007). On Exmoor, wood and/or peat were found to be a good alternative to plastic piling in wide ditches (Fig. 4b). However, when wide ditches are located in very shallow peat, scooping peat out is likely to leave mineral soil exposed and should be avoided. Wood, bales and spoil (Fig. 4c) are recommended instead, to ensure that the mineral soil is not disturbed by the restoration work.

In all peat types, peat blocks (Fig. 4a) are the most widely used method throughout the UK, as it is quick and inexpensive (Armstrong et al., 2009; The Yorkshire Peat Partnership, 2012a). On Exmoor, this technique was found to be particularly adapted for ditches measuring up to 1 m deep and 3 m wide (Supplementary materials Table 1), as this allows the ditch to be blocked with a single scoop of peat, whereas wider ditches requiring additional scoops would need wooden support to improve stability. Peat blocks can be efficient to address small eroding gullies, but tend to wash out in larger natural gullies and anthropogenic grips with high flow energy (The Yorkshire Peat Partnership, 2012a, 2012b). Humified peat was also a better building material than less humified material, due to its low hydraulic conductivity (Tomassen et al., 2010).

Finally, straw bales tend to fail rapidly and introduce nutrients

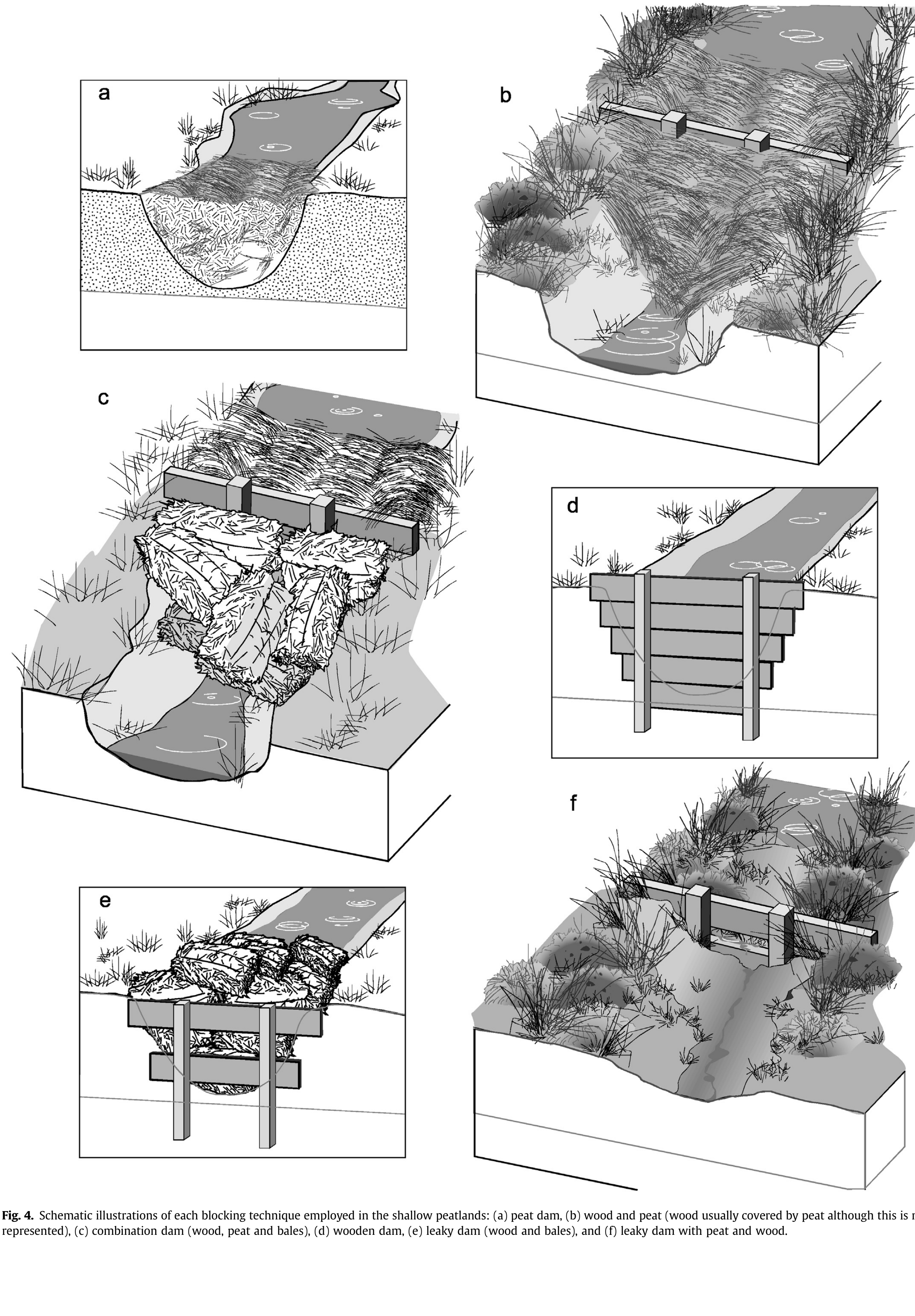

Fig. 4. Schematic illustrations of each blocking technique employed in the shallow peatlands: (a) peat dam, (b) wood and peat (wood usually covered by peat although this is not represented), (c) combination dam (wood, peat and bales), (d) wooden dam, (e) leaky dam (wood and bales), and (f) leaky dam with peat and wood.

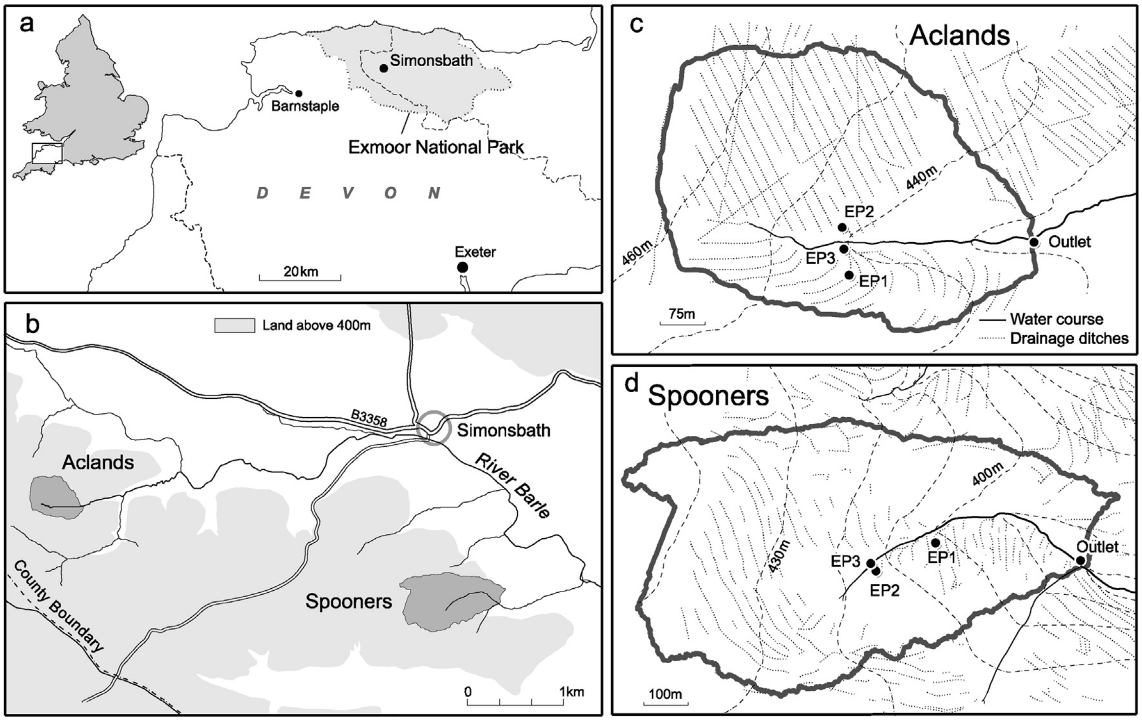

Fig. 5. Location map of Exmoor National Park (UK) (a), and the test catchments of Aclands (18 ha) and Spooners (46.5 ha) (b, c and d), where grey lines indicate the drainage features, and EP1, EP2, EP3 and outlet the monitoring locations by the Exmoor Mires Project.

Table 3
Site and drainage feature characteristics at Aclands and Spooners.

Catchment				Peat	Drains		
Site	Area (ha)	Prevailing slope (%)		Depth (m)	Depth (m)	Width (m)	Length (m)
Aclands	17.9	7.1	Range	0–1.5	0.2–1.3	0.2–3.2	10–306
			Mean	0.3	0.3	0.3	91
			Mode	0.4	0.4	0.6	75
			Total length	NA	NA	NA	7470
			Density (m ha^{-1})	NA	NA	NA	418
Spooners	45.5	6.6	Range	0–1.5	0.2–1.5	0.2–3	5–362
			Mean	0.3	0.5	0.7	40
			Mode	0.2	0.5	1	14
			Total length	NA	NA	NA	8011
			Density (m ha^{-1})	NA	NA	NA	176

and foreign seeds on site, and sheep wool in hessian sacks is now prohibited under the animal waste regulation act (Armstrong et al., 2009). Consecutively, neither technique was used on Exmoor. Similarly, stones are recommended by O'Brien et al. (2007) in situations of "very shallow peat" to address loose peat issues where stakes cannot be used to stabilise the ditch-blocks. Such problem was not encountered on Exmoor.

The location of the blocks (spacing and positioning) is of paramount importance to ensure their efficiency. It should be adjusted depending on the gradient, although it is difficult to draw general rules due to the heterogeneity of the landscape. Spacing will depend on the slope angle and the volume of water to be retained (Armstrong et al., 2009). In theory, levelling the top of the lower dam with the bottom of the upstream dam will allow the water flowing over the block to be held by the downstream dam (Trotter et al., 2005). In the case of gullies, this will minimise flow on bare peat or mineral soil, in turn preventing the undercutting of the dam, and any erosion and damage to vegetation or soil (Trotter et al., 2005). In deep peat, the average spacing of blocks on steep slopes varies between 3 and 4 m; on more homogeneous slopes and lower gradients, blocks could be spaced from 3 m to 8 m apart (Trotter et al., 2005). On Exmoor, the minimum spacing is approximately 7 m to avoid bankside vegetation disturbance, matching The Yorkshire Peat Partnership (2012a) guideline of 7.5 m. Spacing of more than 12 m has been associated with higher failure rates, mostly when peat blocks were used (Armstrong et al., 2009).

4. Restoration of shallow peatlands in practice: the example of two test catchments on Exmoor NP

4.1. Site location

Drawing upon the theory and methods outlined above, this section will demonstrate how practical restoration of damaged shallow peatlands has been achieved at two test catchments in Exmoor National Park, UK (51°9′N; 3°34′W; Fig. 5): Aclands (18 ha) and Spooners (45 ha). The altitude of these catchments ranges between 380 m and 450 m a.s.l.; the 30 year average daily temperature is 10–12 °C (summer) and 4.5–5.5 °C (winter), with an

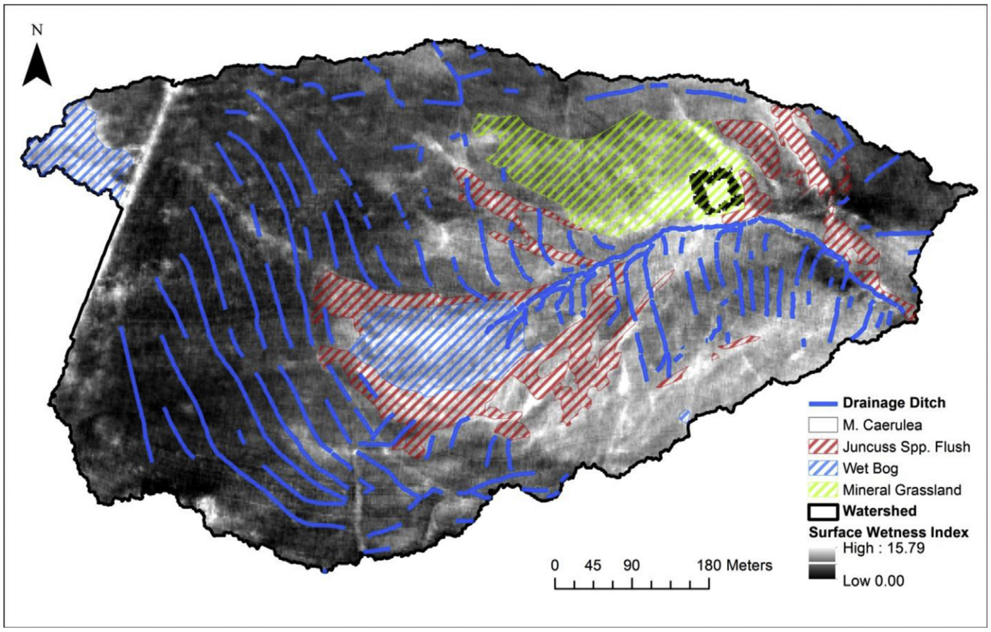

Fig. 6. Drainage ditches, broad vegetation communities and surface wetness index identified on Spooners using remote sensing analysis.

average annual precipitation ranging between 1800 and 2600 mm yr^{-1} (Met Office, 2012).

The average peat depth on Exmoor is ca. 0.33 m (Bowes, 2006), reaching 1.5 m in places (Table 3). The catchments are dominated by *Molinia caerulea* (Purple Moor Grass) (Drewit and Manley, 1997), and other mire and wet heath communities, such as *Sphagnum* spp. and *Eriophorum* spp. There is very little bare peat, but the intensive drainage for agricultural reclamation during the 19th and 20th century has left a very dense network of small ditches (Table 3) located approximately every 20 m in a herring-bone pattern.

An intensive monitoring programme looking at water quantity and quality, biodiversity and gaseous emissions, began in 2011. After ca. 2.5 years of baseline monitoring, the two catchments were restored by ditch blocking in April 2013 (Spooners) and in April 2014 (Aclands). Details of the experimental set up can be found in Luscombe (2014), whilst several publications cover scientific findings (e.g. Luscombe, 2014; Grand-Clement et al., 2014; Gatis et al., 2015).

4.2. The use of remote sensing work to assist with restoration planning

Within the Exmoor Mires Project, the combination of remote sensing data from various airborne platforms was used to give an understanding of the spatially distributed ecohydrological characteristics of the system, and assist in the restoration planning. These data included an airborne Light Detection and Ranging (LiDAR; 0.5 m spatial resolution, May 2009) dataset, alongside airborne thermal imaging data (2 m spatial resolution, May 2009). Additionally, a lightweight unmanned aerial vehicle (UAV) was used to collect very-fine spatial resolution (~5 cm) aerial photographs (R, G, B) of both catchments (March 2011). These datasets were used to characterise the spatial nature of the damaged peat surface, and specifically to map the distribution of linear (i.e. ditches) and geometric features (i.e. possible archaeological features) on the surface (Anderson and Cowley, 2011; Luscombe et al., 2015), map the distribution of major ecological communities (e.g. *Molinia caerulea* tussocks), and derive a spatially distributed index of near surface wetness (Luscombe et al., 2015). The results of these processes, shown for Spooners in Fig. 6, illustrate the relationship between mapped drainage features, the surface wetness index and key vegetation communities. Overall, LiDAR enabled the identification of drainage features, before field validation (i.e. 44 features on Aclands and 89 on Spooners; Anderson and Cowley, 2011). These data have allowed to focus restoration on areas with a higher drainage density and lower surface wetness (Luscombe et al., 2015).

Concerning the HE, remote sensing was useful in helping to identify large features (over ca. 10 m). More specialised interpretation enabled the detection of smaller monuments (i.e. Bennett, 2013), their presence being confirmed by subsequent field survey. In total, remote sensing contributed to the identification of 26 new features across the two catchments (Supplementary materials Table 2), thereby enhancing our knowledge of the historic environment on Exmoor and illustrating the benefits of a holistic approach to environmental conservation.

4.3. Summary of restoration approaches on Exmoor

Overall, the characteristics of the two study catchments (Table 3) show no significant difference in peat depth, although the peat measured along the ditches monitored by the Exmoor Mires Project is shallower at Aclands compared to Spooners (Grand-Clement et al., 2014). However, with a total drainage density of 418 m ha^{-1}, Aclands has been more intensively drained than Spooners (total length of 176 m ha^{-1}). This confirms previous findings and the lower water quality measured at Aclands compared to Spooners (Grand-Clement et al., 2014).

The difference between the drainage densities between sites are reflected in the overall restoration process and the number of blocks used (Table 4). As observed throughout the UK (Armstrong et al., 2010), peat was the most common blocking technique on Exmoor (95% and 87% of the blocks for Aclands and Spooners respectively). Drains are deeper and wider at Spooners (Table 3), explaining the higher proportion of wooden dams used at Spooners (13%) compared to Aclands (4%).

The heavy drainage density of these two catchments compared to the whole of Exmoor (112 m ha^{-1}) is also reflected in the cost of

Table 4
Restoration statistics: total drainage length (m), and number, proportion (%) and density of blocks (blocks per ha) per blocking technique employed on both catchments studied, and for the total area restored on Exmoor from 2013 to 2014 (824 ha).

	Blocks										
	Peat blocks			Wooden blocks			Leaky wooden dams			Total	
	N	%	Block ha^{-1}	N	%	Block ha^{-1}	N	%	Block ha^{-1}	N	Block ha^{-1}
Aclands	788	94.6	44.1	31	3.7	1.7	14	1.7	0.8	833	46.6
Spooners	869	86.9	19.1	129	13	2.8	2	0.2	0.004	1000	22
Exmoor (2013–2014)	8630	86.1	10.5	1361	13.6	1.7	21	0.2	0.03	10,012	12.2

Table 5
Cost of restoration for the two catchments studied and the wider area restored on Exmoor (2011–2012 and 2013–2014).

Area	Area restored (ha)	Price (£ ha^{-1})	Area restored (ha)	Price (£ ha^{-1})
	2011–2012		2013–2014	
Exmoor	390	490	824	306
Aclands	NA	NA	18	811
Spooners	NA	NA	45	473

restoration (Table 5), with £811 ha^{-1} spent on Aclands and £473 ha^{-1} on Spooners (excluding monitoring and land purchase). Because of the lack of material required for peat blocks, and the speed at which they can be built compared to other techniques (i.e. up to 60 peat blocks a day, and 20 wooden dams per day), this technique was found to be the most economical solution for both sites (about £2 per m of ditch).

5. Discussion

The damaging effects of the exploitation of peatlands are found throughout the world. The recent efforts to restore and rehabilitate peatlands are encouraging, and a growing body of evidence points towards the improvement of a whole range of ES, leading to a potential return, for some peatlands, to a state resembling that of functioning mires (Haapalheto et al., 2010). The results presented here focused on the practical restoration of shallow peatlands in the UK, in order to provide land managers throughout the world with guidance based on lessons learnt from the work undertaken on Exmoor. As for any project, the planning of the restoration is the most time consuming but essential to ensure success. Overall, restoration planning should account for other land use, activities and factors such as access to site, landscape, or the historical environment. The combination of remote sensing techniques and walkover surveys illustrated here has proven particularly useful in characterising the landscape and in identifying numerous previously unrecorded archaeological features. This represents a major contribution to Exmoor's historic environment, the full effect of which will only become apparent as future research is undertaken. In terms of the restoration techniques used, it was found that simple peat blocks were the most common measure in both catchments studied, because they are easy, rapid and inexpensive to install. Plastic piling was not used due to the risks of leaking if inserted in the mineral soil and the visual aspect of this method. Finally, a technique using wooden blocks with peat was successfully employed as an alternative to bales, as the baling process can be problematic when the ground is wet and vehicular access difficult, but also because storing bales is not cost or time effective and can substantially delay restoration.

Estimates of the costs of the restoration of the shallow peatlands of Exmoor are highly variable. They ranged from £473 ha^{-1} to £811 ha^{-1} for the two test catchments considered, which is above the average for the whole of Exmoor (£306 ha^{-1}). Comparisons with other projects are, however, difficult because published data are sparse, site specific and equally variable. For instance, a compendium on restoration projects in the UK found a median cost of £1600 ha^{-1} (Holden et al., 2008), converted to £880 ha^{-1} by Chapman et al. (2012) when only practical work is considered. Other published figures are significantly lower, with £300 ha^{-1} for the restoration of Irish cutaway bog (Wilson et al., 2012), and £240 ha^{-1} for grip blocking in England (Moxey, 2011). This variability in costs is partly due to differences in what is included (i.e. monitoring, land purchase, technical costs etc), but more importantly arises from variations in both local factors (e.g. remoteness, terrain and scale) and the level of intervention required between and within projects (Chapman et al., 2012). The results presented above particularly illustrate the impact of peat depth and the characteristics of the drainage network (i.e. length, depth and width of ditches) on the technique to be used, and therefore on cost.

For every restoration project, the question then becomes how to appraise and quantify the benefits from restoration, and whether the process is actually financially viable over the long-term. Cost-benefit analyses of the trade-offs between ES are now increasingly undertaken (e.g. Moxey and Moran, 2014; Reed et al., 2013) because of the growing interest of private companies in funding peatland restoration, and the need to simultaneously consider the multiple benefits provided by peatland restoration (Bonn et al., 2010). However, such exercise remains a very complex task because of the range of physical and economic parameters to consider, as well as their temporal variability and uncertainty. In the case of Exmoor, a coarse estimate has shown that restoration costs are likely to be offset by long-term benefits (Grand-Clement et al., 2013), however this can only be assessed after the effects of restoration are monitored further. Whilst more research is clearly needed on the restoration of other shallow peatlands worldwide, the example of Exmoor shows that peatland restoration is achievable, that the techniques employed here can be used elsewhere, but also that local variability will have an important impact on the restoration process, and on its success.

To conclude, throughout the world, shallow peatlands have largely been overlooked. They are often considered unimportant compared to deeper and more damaged areas, despite being perhaps even more at risk due to their locations on the margins of deeper peat resources, or at the limit of the geographical extent of peatlands, and the scarcity of the resource compared to larger C stores. Preliminary results from shallow and damaged peatlands suggest a negative impact of drainage on certain ES (e.g. Grand-Clement et al., 2014). Moreover, predictions on the effects of future climate point towards drastic changes for marginal and shallow peatlands, putting them outside their bioclimatic envelope, where it is suggested peat formation will cease (Gallego-Sala et al., 2010; Clark et al., 2010), thereby enhancing the need for their restoration and conservation. Overall, lessons learnt from the work undertaken on Exmoor may benefit other shallow peatland restoration projects worldwide and increase our general understanding of the potential recovery of shallow peatlands post-restoration.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jenvman.2015.06.023.

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