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Published in:
Restoration Ecology

Publication date:
2017

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Citation for published version (APA):

Andersen, R., Farrell, C., Graf, M. D., Muller, F., Calvar, E., Frankard, P., & Anderson, P. (2017). An overview of the progress and challenges of peatland restoration in Western Europe. *Restoration Ecology*, 25(2), 271-282. <https://doi.org/10.1111/rec.12415>

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18 **Author contribution**

19 RA wrote the first draft and undertook the systematic review of the EU-LIFE projects; all authors
20 contributed with overview sections relevant to their geographical areas and provided comments and
21 feedback on earlier versions of the manuscript.

22 **Abstract**

23 Peatlands are the most efficient terrestrial carbon store on Earth, and deliver multiple other
24 ecosystem services including climate regulation, water purification, preservation of ecological and
25 archaeological records, etc. Disturbed and degraded peatlands do not provide the same ecological
26 services and thus bear a significant cost to society. Because this cost may be alleviated by
27 appropriate restoration measures, money is being invested in peatland restoration projects around
28 the world. Here we review over 25 years of restoration in Western Europe. First, we provide an
29 overview of techniques used in different contexts and evaluate the status of the evidence-base for
30 restoration outcomes. Between 1993 and 2015 the EU-LIFE nature programme alone invested
31 167.6M € in 80 projects, which aim to restore over 913 km² of peatland habitats in Western
32 European Countries, mostly in protected sites part of the Natura 2000 EU network. This represents
33 less than 2% of the total remaining area of peatlands in these countries, most of which have been
34 impacted to some degree by anthropogenic disturbances. Potential for restoration should be
35 considered in non-designated sites. We reviewed a number of case studies covering a range of
36 restoration approaches used in different parts of Western Europe. We found that published

1 evidence of restoration progress was limited to specific sites/areas, and in many cases lacked
2 baseline measurements and clear goals, i.e. measurable target or contemporary reference(s). We
3 discuss barriers and opportunities to turn the tide for peatland restoration in Western Europe and
4 promote the establishment of robust, standardised monitoring schemes.

5 **Keywords:** Biodiversity, bogs, carbon, ecosystem services, forestry, monitoring

6 **Implication for practice**

- 7 - Peatland restoration has grown in importance in Western Europe over the last 25 years and
8 a vast expertise has been developed both in the science and the practice.
- 9 - Similar approaches are used across Western Europe to restore peatlands. Knowledge
10 transfer and demonstration events should be encouraged to support more efficient
11 technological development and advances in restoration methods.
- 12 - It is critical and urgent to publish existing data and start monitoring a range of ecosystem
13 functions to evaluate restoration trajectories and inform future management.
- 14 - Funding mechanisms supporting long-term monitoring and promoting researchers-
15 practitioners linkages must be established.

16 **Introduction**

17 **Peatland disturbance in Western Europe**

18 Significant portions of the Western Europe support cool, temperate climates with mild and in places
19 oceanic conditions where peatlands have developed over millennia (Fig 1a). Extensive peatland
20 complexes would perhaps still cover vast areas if it had not been for the wide-spread anthropogenic
21 driven land-use conversion that occurred mostly over the last 1000 years. It is estimated that more
22 than half of the peatlands have been lost in Europe (Spiers 1999; Joosten 2012), with the largest
23 losses in the past 75 years (EU 2007). Where peatlands remain in Western Europe, they are greatly
24 reduced in size (Verhoeven 2012). The conflict between conservation and use of peatlands in those
25 countries is particularly prevalent because population densities are high and pressures from
26 competing land-use prevail (Rawlins & Morris 2010; Chapman et al. 2003). Addressing these conflicts
27 requires an integrated understanding of peatland functions and a clear appreciation of how
28 disturbances and restoration of these habitats affect society. On one hand, recent recognition of
29 peatlands' ecosystem services has led to their protection by the Ramsar Convention, the Convention
30 on Biodiversity, EU directives, etc. in the various states. On the other hand, peatlands have long
31 been viewed by many in society as barren wastelands.

32 Systematic drainage of lowland peatlands for improved agricultural yields began in Holland in
33 medieval times, and soon expanded to Germany and beyond (van Dam 2001). In bogs, peat cutting
34 for fuel has a long history in parts of Western Europe (Sjörs 1980; Grünig et al. 1986). Traditional
35 hand cutting has largely been replaced by machines for domestic purposes, and is still widespread in
36 Ireland and Scotland. Extraction for the professional and retail horticultural market still exists in
37 Ireland and Germany, and peat is also used for electricity generation in Ireland. The post-war period
38 led to a systematic programme to drain large areas of peatlands in an attempt to increase the
39 productivity for cultivation and timber production (Sjörs 1980) and for sheep grazing in the UK
40 uplands (Holden et al. 2007). Where these activities have stopped, reduced resilience or even
41 continuing degradation of peatlands is their legacy.

1 Peatlands have also been subject to more subtle, indirect impact from human activities. The rapid
2 development of the steel, coal, fossil fuel and textile industries in Europe had a major impact on air
3 quality during the 19th and much of the 20th century. Sulphur dioxide, one of the atmospheric
4 pollutants resulting from the industrial revolution, is carried in the atmosphere as a dry gas where it
5 dissolves in water drops and contributes to acid rain. In recent decades, atmospheric nitrogen
6 deposition from agricultural and combustion processes has become an extra cause of acidification
7 and eutrophication (Caporn & Emmett 2009; Field et al. 2014). Nutrient enriched waters feeding
8 rewetted drained peatlands can alter carbon and phosphorus cycles, with elevated soluble reactive
9 phosphorus concentrations and pulses of exports to downstream ecosystems (Cabezas et al. 2013).

10 Finally, in the last two decades, a growing demand for renewable energy has created new conflicts
11 as wind energy developments are often sited on deep peat in the UK, Ireland and Spain. For
12 example, in Galicia, wind farms construction in the Xistral Mountains facilitated the spread of
13 invasive species and fragmented the major Iberian upland refuge dominated by blanket bogs (Fraga
14 et al. 2008). These developments are complex and involve many steps where carbon and nutrients
15 are mobilised (Grieve & Gilvear 2008) and where erosion increases (Grace et al. 2013) such as direct
16 removal of peat for the turbine bases and laying of power cables, felling of trees underneath the
17 turbine, and drainage of the peat itself to accommodate roads and other infrastructure (Nayak et al.
18 2010; Smith et al. 2011).

19 **The rise of peatland restoration**

20 Until the 20th century, activities focused on restoration of largely undeveloped peatlands that had
21 been little modified. In recent years, the significance of peatlands to the well-being of society has
22 been more widely recognised (e.g. Bain et al. 2011). In addition to their unique biodiversity and their
23 role as a global carbon (C) store, intact peatlands also contribute to flood alleviation, water storage
24 and purification, provision of recreational spaces and protect the living archive of past
25 environments, among other services (De Groot et al. 2002). Damaged peatlands can't sustain these
26 ecosystem services and bear a significant cost to society, which could be alleviated by appropriate
27 restoration measures. For instance, in Scotland, it is estimated that integrating peatland restoration
28 as a greenhouse gas (GHG) mitigation strategy could provide up to 2.7 Mt CO₂-eq savings per year
29 (Chapman et al. 2012).

30 So far, much of the peatland restoration work in Western Europe has been funded through EU LIFE
31 projects, private companies (e.g. peat extraction companies, water companies, horticulture
32 companies), NGOs and national government programmes (e.g. Keenleyside & Moxey 2011).
33 However, financial incentive schemes which reward sustainable land management to compensate
34 for perceived market related losses associated with a land-use change (Sukhdev & Kumar 2008)
35 make restoration and conservation potentially appealing options. The development of tools like the
36 UK Peatland Code and Payment for Ecosystem Services might enable corporate sponsorship of
37 restoration and management of peatlands on the basis of their carbon balance, climate and other
38 benefits (Bonn et al. 2014).

39 Many countries are now developing national peatland strategies to promote their restoration, and
40 ensure their continued existence and functionality into the future (e.g. SNH 2015; NPWS 2015). After
41 more than a quarter of a century of restoration in Western Europe, we wanted to review the
42 progress that had been made, and identify the challenges laying ahead for peatland restoration.

1 Thus, we aim to 1) examine three decades of investments by the EU-LIFE nature programme in
2 peatland restoration; 2) review techniques and outcomes of restoration undertaken following
3 different types of disturbances through a number of case study areas and 3) identify the main
4 challenges for Western Europe. Since comprehensive reviews of ecological restoration of rich fens in
5 Europe (Lamers et al. 2014) and wetlands more generally (Verhoeven 2014) have been published
6 recently, we have largely focused our review on *Sphagnum* peatlands, including poor and
7 mesotrophic fens.

8 *Peatland restoration financed by the EU-LIFE programme*

9 There were 319 projects funded by the LIFE EU Nature programme since 1993 with the Habitat label
10 “Raised bogs, mires and fens”. We reviewed all of them and excluded those which did not include
11 restoration or which focussed exclusively on rich fens or other wetland types, leaving the 80 projects
12 included in this review (Fig 1b). The most frequent activities in the restoration projects were tree
13 removal (48 projects) and ditch and drain blocking (47 projects). Land acquisition and management
14 plan agreements were also common features of projects between 2000 and 2008 (Fig 2). Vegetation
15 introduction was attempted in <15% of the projects.

16 Between 1993 and 2015, 167.4 M€ (EU-LIFE) and 86.6 M€ (co-funding) were invested in those 80
17 projects, with the aim to restore or improve conditions for over 913 km² of peatland habitats. This
18 represents on average 2800 € ha⁻¹ (Fig 1a, c). The cost-effectiveness of restoration varied between
19 countries, with Austria (31,000€ ha⁻¹) and the UK (1200 € ha⁻¹) and Ireland (750 € ha⁻¹) at opposite
20 ends of the spectrum (Fig 1c). Increased economy of scale in large restoration projects is likely an
21 important factor but lower costs of land purchase and continuity may also contribute to improving
22 cost-effectiveness in Ireland and the UK where the first LIFE-funded peatland projects took place.

23 Although this may be a consequence of the programme’s priorities, monitoring was largely focused
24 on target species (86% of the projects). Far fewer projects assessed other ecosystem services (Fig 3).
25 In general, monitoring was limited to the sites under restoration (i.e. no reference sites) and not
26 comprehensive enough for statistical analyses. In many instances final reports and associated data
27 were not publicly available making a general conclusion about the “success” of the programme’s
28 investment impossible to reach.

29 *Restoration of extracted peatlands (Germany, Ireland, Switzerland, UK)*

30 From the early 1980s, extensive research conducted in Ireland, jointly led by a team of Dutch and
31 Irish scientists (Schouten 2002) has provided a detailed understanding of how hydrological
32 processes support peat formation in raised bogs. Findings from this research led to the development
33 of damming, drain blocking and lagg management strategies, implemented on a number of bogs
34 across the Irish Midlands (Schouten 2002). This work has been more recently further developed
35 using remote sensing coupled with local hydrological data to prioritise areas for restoration (Flynn et al.
36 2015; Mackin et al. 2015; NPWS 2015).

37 Basic restoration techniques, including drain blocking and damming, have been carried out on bogs
38 owned by the State peat extraction (Bord na Móna) and forestry companies (Coillte). Since 2009,
39 Bord na Móna has undertaken restoration over 1,175 hectares of damaged raised bog using drain
40 blocking informed by detailed topographic mapping (Bord na Móna 2010 & 2016). Much of these
41 have been earmarked to compensate for the loss of active raised bogs in Natura 2000 sites in
42 Ireland, and ongoing marginal cutting in protected raised bogs has further stimulated restoration

1 activities. Where industrial peat extraction from raised bogs exposes deeper fen peat layers the
2 target of restoration (drain blocking and damming) is fen habitat (Bord na Móna 2010 & 2016).

3 Similarly, since 1981, the Lower Saxony Bog Protection Program has obliged horticultural peat
4 companies in Germany to restore peatlands after extraction activities ceased, which prompted the
5 development of peatland restoration techniques (Blankenburg 1994; Blankenburg 2004) similar to
6 those developed in Ireland. The focus is on rewetting the site by leveling the surface, constructing
7 dams, infilling and compaction of ditches and drains, constructing outlets to prevent damage from
8 runoff and, creating facilities for regulating water levels (Blankenburg & Tonis, 2004). It is assumed
9 that if the hydrology is restored, typical bog plant communities will spontaneously return
10 (Blankenburg & Tonis, 2004). To date, restoration has targeted 15,000 ha of peatlands and by the
11 year 2040, a further circa 12, 000 ha will be under restoration in Lower Saxony (Schmatzler 2012).

12 A study of over 71 German peatlands where restoration had been undertaken revealed that typical
13 peatland plants returned to over half of the sites (Graf et al. 2015). However, even after 30 years,
14 certain plants, dominant in undisturbed bogs, did not return spontaneously to many sites.
15 *Sphagnum* mosses that are essential for the functioning of bog ecosystems, were only represented
16 by a few dominant hollow species (*Sphagnum cuspidatum* and *S.fallax*), while lawn and hummock
17 species were absent (Graf et al. 2015). Additionally, vascular plants, such as *Andromeda polifolia* and
18 various *Vaccinium* species, did not spontaneously recolonize these sites. Peatlands used for
19 agriculture prior to peat mining, were dominated by *Juncus effuses* following restoration, most likely
20 due to phosphorus fertilizer residues (Rosinski 2012). It was suggested from an earlier study in the
21 Netherlands that high N:P ratio (>16) limits *Sphagnum* growth, and that other peat characteristics
22 typical from cut-over sites, such as high lignin content, would also inhibit related biogeochemical
23 processes such as methane production (Smolders et al. 2002).

24 A limitation to reintroducing peatland species is a lack of donor material, because the few natural
25 peatland remnants are strictly protected reserves where harvesting material is not permitted. In
26 addition, the relatively thin layer (50cm) of residual peat left on site as prescribed by law leads to
27 fluctuating hydrological; fatal for *Sphagnum* species. Current research on peatland restoration in
28 Germany is examining reintroduction of species that do not return spontaneously and similar trials
29 are underway in Ireland. *Sphagnum* cultivation may provide a solution in the future for extracted
30 peatlands in Germany (Gaudig et al., 2014).

31 In Ireland, when stable hydrological conditions are achieved through re-wetting of industrially
32 extracted sites and where vegetation re-colonisation is successful, it leads to short-term reductions
33 in CO₂ emissions and could increase C savings by promoting new C sequestration (Wilson et al. 2012;
34 Wilson et al. 2013). On the other hand, rewetting is also linked with the creation of hot spots for
35 methane, associated to plant species with aerenchymae, high water level and elevated
36 temperatures (Wilson et al. 2009). Bord na Móna, Coillte, Environmental Protection Agency,
37 National Parks and Wildlife Service (NPWS) and Irish Peatland Conservation Council are collectively
38 carrying out further vegetation and GHG monitoring on rewetted and peatlands under restoration as
39 well as rehabilitated cutaway bog areas. Such monitoring should be extended out to all types of
40 land-use, over longer time periods and in other geographical regions where restoration of extracted
41 peatlands is happening.

42 *Restoration of isolated and remnant peatlands (Belgium, Switzerland, Spain)*

1 In Belgium, peatlands are not a dominant feature in the landscape but are confined to small areas
2 (Frankard et al. 1998). Due to development pressure and land-use changes, some of these areas
3 have become isolated and disconnected. Three EU-LIFE-Nature projects were first established
4 between 1995 and 1998 to safeguard the last large areas of rich fens, the largest and best developed
5 *Rhynchosporion*, and some small transition mires and relicts of bog woodland. A further six LIFE
6 projects have since been established to restore large areas of raised bogs, transition mires, acidic
7 fens and bog woodlands. Restoration has already been undertaken in more than 5,000 ha of
8 peatlands, mainly degraded drained bogs covered with *Molinia caerulea*, but also in afforested bogs
9 with spruces and wet heaths (Fig 1a) with an aim to improve the conservation status. Site networks
10 have been fully redesigned to ensure natural re-colonisation processes and regional population
11 dynamics (Plunus et al. 2014).

12 Similar restoration methods to the ones described for peat extraction were used: raising the water
13 table by ditch blocking; levelling areas by removing the peat surface or by rotovating or scraping
14 vegetation and subsoil; introducing *Eriophorum* species *Sphagnum* fragments on bare peat, and re-
15 wetting heavily cut-over bogs using peat, clay or PVC dams and/or by re-modelling the peat surface
16 to form lagoons. Other techniques included tree and shrub removal or mulching and sheep grazing
17 on inactive areas as a means to control *Molinia caerulea* (Frankard et al. 1998; Frankard 2001 &
18 2012).

19 Biological and hydrological effects of the large scale restoration measures taken as part of LIFE
20 projects are currently investigated. Detailed biological monitoring programmes have already shown
21 a positive effect within each project and on the regional conservation status for vegetation (Frankard
22 2012 & 2016), birds, and insects (Ghiette, 2012). More specifically, in some of the acidic fens, the
23 number of Odonata species recorded doubled in less than five years (Dufrêne et al. 2011), with some
24 peatland specialists *Aeshna juncea*, *Leucorrhinia dubia*, *Sympetrum danae*, and *Orthetrum*
25 *coerulescens* making a comeback within the first five years (Kever et al. 2014; Parkinson 2010).
26 Nevertheless, for all taxa, regression of some typical species and connectivity problems still remains,
27 meaning that small and isolated populations of the typical species are threatened by inbreeding
28 depression and extinction debts. Other ecosystem functions such as GHG emissions are not currently
29 being monitored in those systems.

30 *Restoration of mountain peatlands*

31 The Jura Mountains shelter 495 peatlands with a total area of 5347 ha. Among them, 73 are in
32 Switzerland covering an area of 1246 ha, thus the majority is in France. In the Jura, as in Spain
33 peatlands are not a dominant feature. Nevertheless, in both cases they play important roles in mid-
34 elevation mountains (Derex & Grégoire 2010), are historically important (Cholet & Magnon 2010),
35 and provide a refuge for rare and local species and habitats (Fraga et al., 2008). In the Jura, influence
36 of calcareous rocks means that both acidic and alkaline peatlands co-exist, whereas in Spain, raised
37 and blanket bogs are the dominant feature.

38 Mountain peatlands historically provided local human populations with an easy source of fuel, which
39 led to important habitat losses. In France, protection measures were adopted in most regions in the
40 1980s, soon followed by restoration initiatives such as LIFE Programme 'Tourbières de France' in
41 1995-99. Initial work focused on re-meandering creeks inside the peatlands. The projects were
42 problem-driven, targeting species of concern or fighting encroachment. More recently, hydrology

1 was increasingly considered the main factor to be addressed (Grosvernier & Staubli 2009) and
2 became a priority in the most recent LIFE-funded restoration initiative, 'Jura Peatlands / Tourbières
3 du Jura', which started in 2014 and targets 60 mountain peatlands. Prior to restoration, hydrological
4 studies, including LIDAR flights, were set up to establish how the different disturbances affected the
5 functioning of peatland and inform management. An important benefit of continued investment in
6 peatland restoration in the Jura was the development of locally-based specialized contractors and
7 machinery, which also increases cost-efficiency.

8 Restoration techniques in the Jura now include drain blocking using wood panels and sawdust or
9 peat to rehabilitate peat extraction areas. Hydrological surveys show a positive rise of the water
10 level and reduced water table fluctuations. In Spain, restoration efforts started more recently.
11 Monitoring isn't always included, and published results are largely inexistent, but a study showed
12 that in at least one site, *Sphagnum* recovered following drain blocking (Juan Ovejero, 2014). Like
13 with previous restoration examples, further assessments over a longer time-period including other
14 ecosystem functions should be implemented in the future.

15 *Restoration of afforested peatlands (Uk, Ireland, Belgium, Denmark, Germany, Austria)*

16 From the 1950s onwards, coniferous trees were planted over large open peatlands perceived as
17 "unproductive" and by 1990 >800,000 ha (ca.20%) and > 200,000 ha (ca.16%) had been planted in
18 the UK (Artz et al. 2014) and in Ireland (Farrell 1990; Renou and Farrell 2005), respectively. Forestry
19 plantation of exotic conifers also replaced traditional agro-pastoral practices, and poor management
20 led to encroachment by shrubs and trees in peatlands of many countries including Belgium,
21 Denmark, Germany and Austria.

22 In addition to threatening the C store underneath the plantations (Cannell et al. 1993), this large-
23 scale land-use conversion also fragmented previously open and connected landscapes. In the Flow
24 Country of Scotland, the negative impact on protected bird species in the neighbouring unplanted
25 areas (Wilson et al. 2014) was strong enough evidence to influence policy: new guidance now
26 prevents planting on peat >50cm and promotes restoration around designated areas for peatlands in
27 Scotland (Forestry Commission Scotland (FCS) 2014). Since 1997, in state and municipality forests of
28 Wallonia (Belgium), it is also forbidden to drain peaty soils and to afforest or to re-stock soils
29 covered with >40cm of peat and in the immediate surroundings of springs.

30 In the UK, the first large-scale attempts of forest-to-bog restoration were undertaken in the mid-
31 1990s in the Flow Country of Caithness and Sutherland, and were soon followed by other initiatives.
32 Initially, a combination of drain blocking and felling-to-waste was the preferred method, as the trees
33 were small enough to be rolled in the furrows. Similar approaches were used in Ireland by Coillte for
34 removal of 1,000 ha of plantations from raised bog areas. Over time, trees initially planted over the
35 peatlands grew, the canopy closed and needle litter accumulated at the detriment of bog species
36 underneath. The restoration techniques had to be adjusted and specialist equipment was developed
37 (e.g. low-ground pressure harvesters). New techniques currently trialled include whole tree
38 harvesting, brash removal, and mulching (similar to that used in Belgium for remnant peatland
39 restoration). More recently, a combination of stump flipping and ground smoothing has been trialled
40 (SPR, 2015).

41 In areas on a slope steeper than three degrees where trees had been felled and left on site in
42 furrows, recovery was slow. There, combinations of brash crushing and further drain blocking are

1 being tested to improve hydrology and to speed up the recovery of key species like *Sphagnum* (Neil
2 Cowie, RSPB Scotland, personal communication). There are some published studies on the initial
3 effect of restoration and long-term recovery of the ecosystem functions following tree removal from
4 peatlands (Table 1); but only a fraction includes baseline monitoring. Where ground work or
5 decomposition of brash and needle litter could impact adjacent freshwater rivers inhabited by key
6 species like the freshwater pearl mussel (*Margaritifera margaritifera*) or the Atlantic salmon (*Salmo*
7 *salar*), the ecological and economic implications are far from fully assessed. A key issue encountered
8 following restoration is the aggressive regeneration by seedlings of Sitka spruce and Lodgepole pine
9 (*Pinus contorta*) or colonisation by birch (*Betula sp.*). Controlling regeneration is now an expensive
10 ongoing management requirement and better solutions are sought to reduce the costs.

11 Many forestry plantations on peatlands in Western Europe are now coming to the end of their first
12 rotation, at a time when national forestry targets, GHG reductions targets and biodiversity targets all
13 need to be met. Nevertheless, re-stocking of a plantation on peatland is incompatible with
14 restoration of peatland habitat. Thus, evidence-based priority setting and clear guidelines need to be
15 in place to enable a rigorous assessment of which sites – if any – are suitable for re-stocking and
16 which ones should be restored and how.

17 *Restoration of eroded peatlands (UK)*

18 In the UK, the blanket bogs of the Peak District National Park and Southern Pennines to the north
19 have been severely degraded by atmospheric deposition coming from industrial pollution and
20 wildfires (Anderson et al. 2009; Caporn and Emmett 2009). These factors have contributed to a
21 range of problems, the most extreme being the loss of *Sphagnum* and other bryoflora from the
22 blanket bogs due to sulphur pollution (Lee 1998). Another issue was the significant decrease of the
23 pH (<3) and subsequent lack of regeneration of the vegetation after wildfire in the face of high
24 grazing levels (mostly of sheep). The outcomes have been extensive areas of bare ground and peat
25 erosion, sometimes down to the bedrock, which covered as much as 33 km² of the Peak District a
26 few decades ago, combined with severe gullying and erosion of the bog surface (Phillips et al. 1981).
27 The exposure and instability of bare peat accelerates erosion and the increase in gullying, which
28 drains water from the bog causes further desiccation of the remaining peat and vegetation in dry
29 periods and impacts on water provision downstream (Evans et al. 2014). Concerns over carbon loss
30 and water quality in streams receiving runoff have also arisen following drainage and management
31 such as controlled burning (Brown et al. 2014).

32 Restoration targets have to reflect the different end users with many and sometimes conflicting
33 interests including biodiversity, farming, water supply, carbon storage, recreation and education.
34 The priority for restoration in the Peak District was initially to stabilise and revegetate bare peat to
35 stop the loss of peat and to provide a better habitat for biodiversity, stock grazing and grouse
36 production. Methods were pioneered in early trials of the Moorland Management Project (Anderson
37 et al. 1997), but since 2003 have been scaled up to much larger areas by the Moors for the Future
38 Partnership (Anderson et al. 2009) (Table 2). Applications of lime and fertiliser (to combat the low
39 pH), nurse grass seed (to stabilise the surface), heather seed in the form of brash and geotextile
40 have transformed eroding ground from vast peat flats into stable, heather-dominated vegetation,
41 which has substantially slowed peat erosion (Worrall et al 2011). Wood, stone, peat and plastic
42 dams, together in places with re-profiling to remove over-steep peat faces, have all been trialled in
43 gullies of various sizes to slow the water movement and raise water tables, thus re-wetting the peat.

1 Despite these major improvements, some of the blanket bogs remain covered with vegetation not
2 typical of peatlands, but rather extensive areas of near monocultures of heather (*Calluna vulgaris*),
3 purple moor grass (*Molinia caerulea*) or cotton grass (*Empetrum angustifolium* and *E. vaginatum*). In
4 the past 10 years, *Sphagnum* has naturally, albeit slowly, been returning to the bog surfaces,
5 probably a result of declining sulphur pollution and rain acidity (Carroll et al. 2009) and reduced
6 sheep grazing levels. As conditions improve for *Sphagnum*, major re-introduction efforts are
7 undertaken in order to speed-up the recovery and increase the diversity of species (Moors for the
8 Future 2015). Like for extracted peatlands in Germany, there is a lack of source material locally, so
9 translocation from other parts of the country and also the novel approach of planting micro-
10 propagated *Sphagnum* (Hinde et al. 2010) are being trialled. Other bog species including *Eriophorum*
11 species and *Empetrum nigrum* are also being added as plugs to revegetated sites, in an attempt to
12 increase diversity, help restore the ecohydrology and generate active peat again (Moors for the
13 Future, 2015).

14 Up until now, funding for eroded peatland restoration largely came from a combination of EU-LIFE
15 funding, public funding through agri-environment schemes and private companies. Sustained
16 funding to support restoration efforts and monitoring will still be needed to achieve the longer term
17 goals of reinstating functional blanket bogs in those eroded areas.

18 *Challenges for peatland restoration in Western Europe: the road ahead*

19 Here we formulate common challenges for peatland restoration in Western Europe as questions that
20 we hope will be tackled by the next generation of peatland scientists.

21 *1) What is the best way to restore degraded peatlands?*

22 Peatland systems, the pressures and threats to their integrity and the approaches to restoration are
23 generally similar between countries within Western Europe. Shared practical knowledge,
24 technological advances, research and monitoring should be facilitated with all stakeholders to
25 improve methods more efficiently. On the ground, this can be achieved through knowledge transfer
26 which promotes the development (and implementation) of best practice (Rawlins & Morris 2010).
27 Further mechanisms must be developed to ensure that large- and small-scale restoration projects
28 are integrated into openly accessible national inventories.

29 *2) How successful has restoration been?*

30 Monitoring ecosystem functions against baselines and references is necessary to assess “success” of
31 restoration, but is currently mostly lacking in Western Europe. The costs associated with long-term
32 monitoring of ecosystem functions are often prohibitive, and difficult to fund through existing
33 schemes which are either too short (<5 years) or too restrictive (i.e. do not support monitoring)
34 (Halme et al. 2013). We suggest that establishing systematic and standardised long-term monitoring
35 and research programmes targeting functional elements (e.g. Nwaishi et al. 2015), with appropriate
36 baseline and controls or at least reference sites would allow the development of a common
37 language when talking about “success”. For monitoring large-scale restoration projects where
38 ground-based measurements are unrealistic, developing cost-effective methods (e.g. remote sensing
39 approaches linking vegetation and GHG fluxes) and proxies is also critical.

40 *3) How will disturbed and systems under restoration respond to global changes?*

41 In Europe, shifts in plant distribution as a consequence of climate change are expected to be
42 greatest in the transition between the Mediterranean and Euro-Siberian regions (Thullier et al.

1 2005). Understanding where peatlands are most likely to remain functional, or where disturbed sites
2 are at risk of crossing irreversible thresholds is essential to guide actions that build and/or
3 strengthen ecological resilience (Gillson et al. 2013). We advocate an integrative framework to
4 restoration and conservation combining paleoecology, present day ecology and climate modelling.

5 4) *How much is peatland restoration worth?*

6 Empowering private owners to change their way of using peatland habitats is possible (Rawlins &
7 Morris 2010), but it can be challenging even where grant schemes are available. In part, this is
8 because restoration of peatlands can require a large upfront capital investment. As well as direct
9 repayment, the return on the investment should come from benefits arising from ecosystem
10 services (Bonn et al. 2014) and outweigh the loss of services provided by the damaged peatland (e.g.
11 timber, fuel or food). However, these are not often expressed as tangible outcomes to the
12 landowners. By quantifying ecological benefits arising from peatland restoration in economic terms
13 and communicating them more effectively, we can influence future investment (Reed et al. 2014)
14 and inform the selection of cost-effective areas to be restored (Adame et al. 2015).

15 **Conclusion**

16 Peatland restoration should be attempted where it is feasible. However, in some cases, extensive
17 damage combined with changes in environmental conditions mean that bringing back functional
18 conditions may be impossible to achieve – at least not without investments which society may not
19 be inclined to make. This review highlighted that in Western Europe, peatland restoration activities
20 have been mostly undertaken in protected areas. But larger areas of non-protected peatlands are
21 still being extracted, drained for agriculture and forestry and/or abandoned. The potential economic
22 value of restoration of these marginal soils and areas outlying nature reserves should be explored.

23 Large investments of public money have been made in peatland restoration in Western Europe in
24 the last 25 years. To be accountable for these investments, we have a responsibility to understand
25 whether the objectives laid out prior to interventions and management have been reached and to
26 take action where they have not. Existing long-term datasets should be published and accessible to
27 help increase our knowledge and develop adaptive management methods more readily. Because
28 they are mostly lacking, we advocate for support towards the development and implementation of
29 standardised, long-term monitoring schemes targeting multiple ecosystem services delivered by
30 peatlands.

31 **Acknowledgements**

32 We thank L. Rochefort for suggesting the idea of a global review and for initial discussion with
33 Restoration Ecology EB. RA's research is supported in part by Leverhulme Trust RPG-2015-162 grant.

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1 Table 1. Current knowledge and published evidence of impact of restoration of afforested peatlands.
 2 WT = Water Table

Ecosystem service	Variable monitored	Key finding	Reference
Support of biodiversity	Number of invertebrates, birds, amphibians and mammals	Ongoing monitoring, no published data yet	Cowie N and Hancock M, personal communication
	Vegetation	Following restoration forest mosses declined and <i>Eriophorum vaginatum</i> increased. <i>Sphagnum</i> cover increased but initially restricted to furrows. Ongoing monitoring with further data on recovery of <i>Sphagnum</i> species is unpublished.	Anderson 2010
	Testate amoeba	Communities in older sites shift away from afforested sites and towards dry open blanket bog sites	Creevy 2014
	Diversity of archae, fungi and bacteria	Ongoing monitoring using next generation sequencing	Artz R.R.E, personal communication
Regulation of pest and diseases	Number of ticks	Forest-to-bog restoration reduced tick numbers and thus the potential for transmission of tick-borne diseases	Gilbert 2013
Supporting services	Nutrient cycling	N mineralization is increased under brash mats	Asam et al. 2012
	Nutrient export	P export is increased immediately after felling and decreases after ca. 4 years post-felling	Rodgers et al. 2010; O'Driscoll et al. 2014; Clarke et al. 2015, Nieminen et al. 2014
Water regulation	Hydrology	Restoration raises the WT levels but not to levels similar to undisturbed blanket bogs. Damming furrows raises the WT level further when used in combination with felling. In lowland raised bog, leaving brash or trees on site after felling reduced evaporation. Windrowing increases total suspended solid in outflow.	Anderson 2010 Clarke et al. 2015
	Water quality	Felling caused changes in seasonal cycles of biologically active (C, Si, P) and organically complexed (Fe, Al) elements. The decomposition of felling residues leaches K and C and the disturbance and partial mineralisation of shallow peat soils releases P, Fe and Al. Where disturbances during afforestation has reached the mineral ground under the peat mass, this could lead to long-term elevated concentrations of Al and Mn in receiving streams.	Müller et al. 2015 Müller & Tankere Müller 2012

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2 Table 1. Continued

Ecosystem service	Variable monitored	Key finding	Reference
Climate regulation	Carbon fluxes	Ongoing monitoring of GHG emissions using Eddy Covariance and closed chamber techniques	Hill, T. & Subke, J-A., personal communication
	Aquatic carbon fluxes	Highest export occurs during storm events. Export depends on catchment properties.	Vinjinli 2012
	Aquatic carbon cycling	Ongoing monitoring on carbon dynamics in pools	Turner E, personal communication
	Carbon stocks	C stocks are highly variable over short distances, assessing impact requires local comparisons	Ratcliffe 2015
	Litter decomposition (needles)	Decaying spruce needles are sources of P and metals to the peat and potentially to water courses	Asam et al. 2012
	Litter decomposition (peat forming species)	Ongoing monitoring on rate of decomposition for peat forming species	Artz R.R.E, Personal communication
	<i>Sphagnum</i> growth	Ongoing monitoring on annual growth	Payne R. Personal communication

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4

- 1 Table 2. Restoration projects targeting bare and eroded peatlands in the UK and details of
 2 management undertaken by project partners.

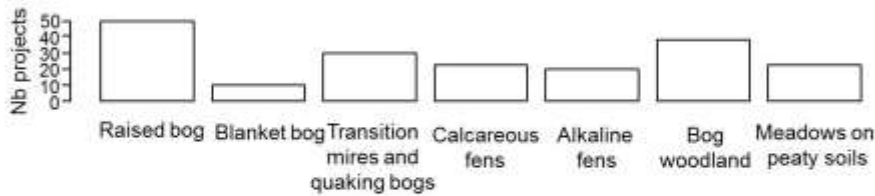
Location	Project partners	Year	Area restored (km ²)	Stabilising	Reprofiling	gully blocking	Ditch blocking	Re-vegetating	Controlled grazing	Fencing
Peak District moors, South Pennines	Moors for the future	2003	NA							
Bleaklow & Black Hill Peak District, Rishworth & Turley Holes, South Pennines	Moors for the future	2010-15	8							
South Pennines from Windy Hill transmitter (S of M62) to Walsden and Todmorden	Moors for the future	2011	NA							
Ashop and Alport R catchments Peak District	Moors for the future	2010-15	NA							
Yorks Dales, North York Moors, Pennines Bradford/Keighley area	Yorkshire Peat Partnership	2009	213.8							
Upper Conway catchment, Ysbyty Estate	National Trust	2008-12	>30							
Orkney	Highland Park Distillery	1997	18.75							
Goyt, Longdendale, Peak District & Bowland	SCaMP, United Utilities	2005	55							
Cumbria	Cumbria Wildlife Trust	2013	1							
Malham Tarn	National Trust		NA							
N Pennines	N Pennines AONB Partnership	2006	94.6							
16 sites in Yorkshire	Yorkshire Water Services, Moors for future	2004	32.5							
Four sites on Dartmoor	Dartmoor mires project	2010	0.55							
Abergwesyn Estate	National Trust		26.5							
Kinder Scout	National Trust		NA							

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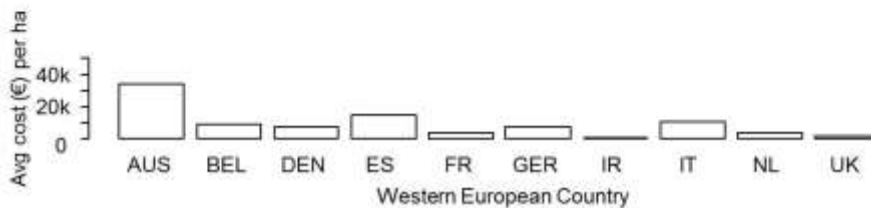
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b. Types of peatlands restored through EU LIFE projects



c. Cost per area of EU LIFE projects involving peatland restoration



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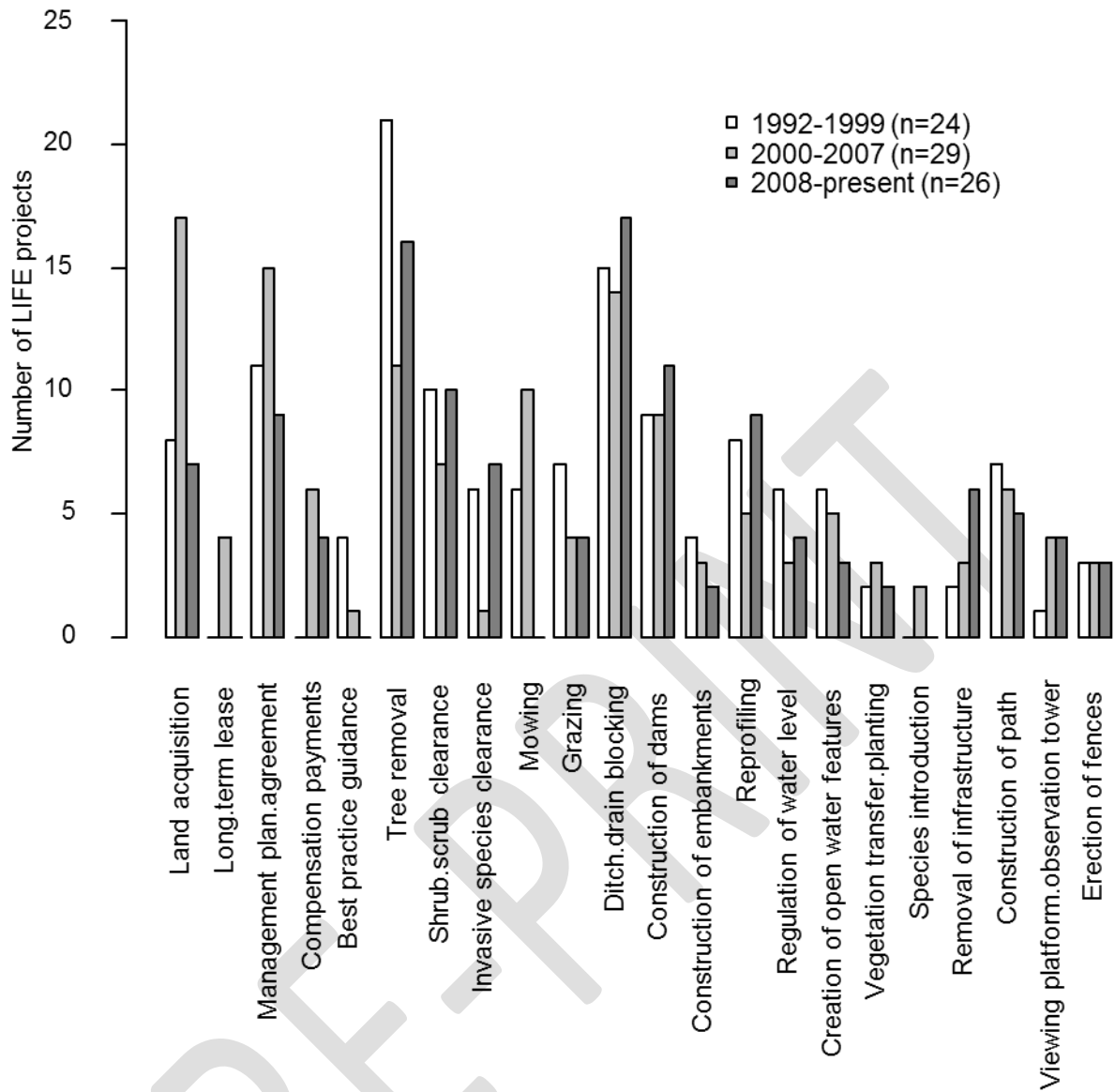
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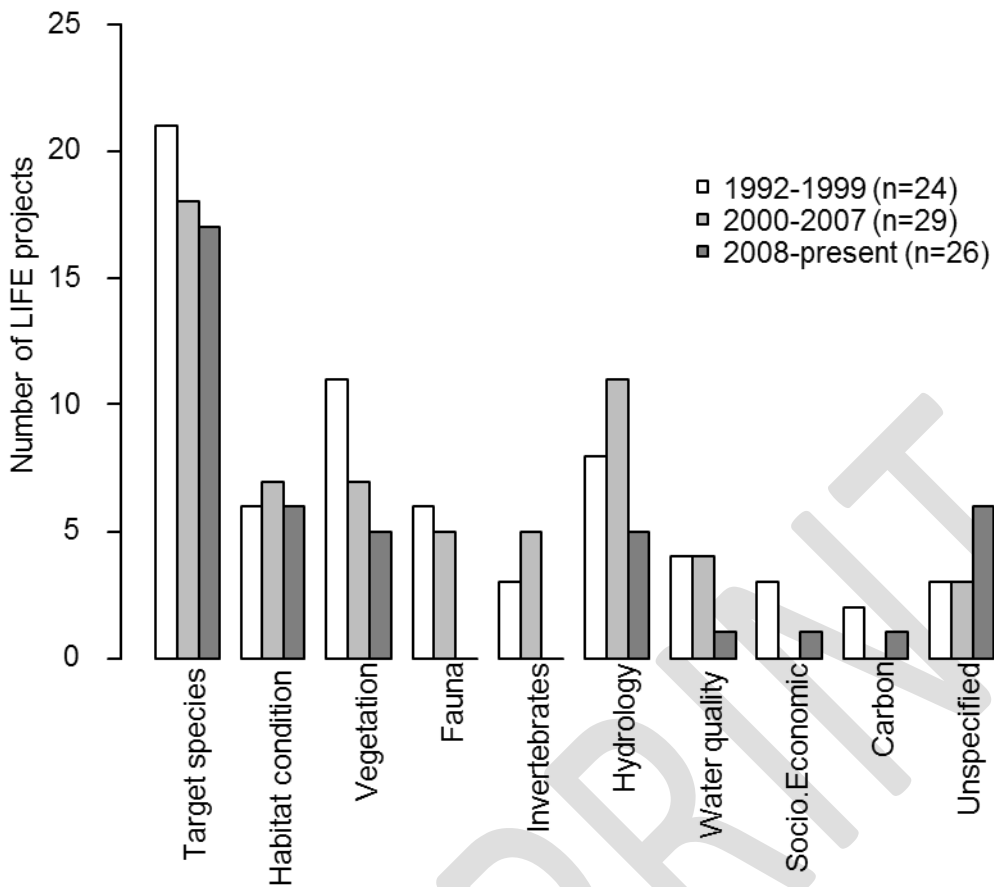
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Figure 1a) Total area of peatlands (km²; source: Montanarella et al. 2006) in Western Europe with area targeted by restoration (EU-LIFE Nature programme only) in brackets. Countries in grey are included in this review; b) Types of peatlands targeted by restoration. Although we excluded rich fens, many projects included more than one site and more than one peatland types, but the majority were *Sphagnum* dominated; and c) Average cost in Euro per ha. The data comes from 80 projects in Western European Countries targeting peatland habitats funded by EU-LIFE Nature between 1997-2015 (Source: EU-LIFE, 2016).



1

2 Figure 2. Range of management undertaken as part of EU-LIFE projects (n =80) targeting peatland
 3 habitats in Western Europe between 1997 and 2015. (Source: EU-LIFE 2016).



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2 Figure 3. Monitoring undertaken as part of EU-LIFE projects (n =80) targeting peatland habitats in
 3 Western Europe between 1997 and 2015. (Source EU-LIFE 2016).

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