RECOVERY OF THE VEGETATION OF A CUTOVER RAISED BOG IN IRELAND FOLLOWING REWETTING MEASURES

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ABSTRACT

Restoration works involving the blocking of drains with peat dams and the construction of a marginal berm along the edge of the cutover on Killyconny Bog in Co. Cavan, Ireland were carried out in the mid to late 2000s. Vegetation change between a pre-restoration baseline and surveys carried out 7–13 years post-restoration are assessed and demonstrate that 5.0ha of *Sphagnum*-rich regenerating bog vegetation has developed across the 26.9ha study site since restoration works were implemented. Although the restoration measures have triggered *Sphagnum* regeneration, increased the number of positive indicators species of Active Raised Bog (ARB) and initiated the process of peat-formation, the vegetation still lacks the presence and/or abundance of some critical ARB indicators. Moreover, 56% of the site is still dominated by vegetation with a low *Sphagnum* cover; 44% by *Calluna vulgaris* dominated vegetation and 12% by *Molinia caerulea* dominated vegetation. The key importance of topography in determining restoration potential is highlighted as extremely fine variations in topography appear to have resulted in significant differences in the vegetation that has developed. Any further increase in the area of regenerating bog on the cutover is likely to require enhanced restoration works such as cell bunding and additional marginal berms, the design of which will be informed using the modelling techniques outlined. Although not yet considered ARB habitat, the 19% of the Killyconny cutover that is classed as regenerating is clearly of conservation significance as a peat-forming habitat that supports assemblages of several specialist species and demonstrates how restoration works that raise water levels can initiate *Sphagnum* regeneration in a relatively short period of time.

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INTRODUCTION

Wetlands are globally important ecosystems that provide critical services in the areas of climate regulation, biodiversity, hydrology and human welfare (Ramsar Convention Secretariat 2016). However, it is estimated that 54–57% (but possibly as high as 87%) of wetlands have been lost worldwide since 1700 (Davidson 2014) with losses occurring at a much faster rate during the twentieth and early twenty-first centuries. A wetland type of global significance is peatland, which accounts for an estimated 33% of the world's wetland cover (Parish *et al.* 2008) and despite covering just 3% of the global land surface, are considered the earth's most important terrestrial carbon store and important in global carbon biogeochemical cycling. A peatland system of particular importance is 'Active' (i.e. peat-forming) Raised Bogs (ARB). These habitats have disappeared almost entirely in temperate regions as a result of land reclamation for agriculture and forestry, fuel production, supply of horticultural products and urbanisation (Moore 2002). They are thus defined as priority Annex I habitats under the EU Habitats Directive (92/43/EEC), while 'Degraded Raised Bog still capable of natural regeneration' (DRB) is also an Annex I habitat. EU member states are obliged to protect Annex I habitats by including a proportion of them in Special Areas of Conservation (SACs); priority Annex I habitats are those in danger of disappearance and a large proportion of whose natural range falls within the EU. Peatlands are now among Europe's most threatened ecosystems and the conservation and restoration of remaining areas is an international nature conservation priority (Regan *et al.* 2020).

In Ireland, peat soils cover up to 21% (Connolly 2018) of the landscape and occur across a distinct biogeographical climatic gradient, spanning upland and low-lying ombrotrophic bogs to groundwater-fed fens. Despite significant losses, Ireland contains one of the highest concentrations of wetlands in Europe and approximately 50% (Foss *et al.* 2001) of the remaining area of raised bog habitat in the Atlantic region of north-west Europe. However, recent mechanised commercial peat extraction, combined with hundreds of years of marginal domestic turf cutting, has resulted in the loss of more than 80% of the original raised bog area and the drying out of much of the remainder. As a result, only 9% of the original raised bog area is considered to be suitable for nature conservation and less than 1% of this area is ARB (National Parks and Wildlife Service (NPWS) 2018). Furthermore, much of the structurally intact high raised bog habitat has low restoration potential due to relatively steep slopes from drainage-induced peat settlement. Cutover bog can therefore sometimes have a higher potential for restoration than some areas of intact high bog due to flatter terrain (Mackin *et al.* 2017a). Cutover raised bog habitats are widespread in Ireland and approximately 9,100ha is included in the protected raised bog network of SACs and Natural Heritage Areas (NHAs) (NPWS 2018). Restoration of a proportion of this area would therefore significantly increase the biodiversity value of Ireland's peatland resource and contribute to land-based climate change mitigation measures, achieved by carbon sequestration from peat-forming habitat (Regan *et al.* 2020). It would also play an important role in helping Ireland meet its conservation targets for ARB as set out in the *National raised bog special areas of conservation management plan 2017–2022* (NPWS 2018). The plan sets the target for the area of ARB in the national raised bog network at 3,600ha, which is derived by summing the area of ARB and DRB habitat within the current SAC and NHA network when the Habitats Directive came into force in 1994. Hydrological modelling suggests that this target is not achievable on the high bog alone, and thus to meet the ARB national conservation objective, it will be necessary to not only restore ARB where possible on high bog, but also to restore peat-forming conditions (and eventually ARB) on up to 448ha of cutover areas (NPWS 2018).

The Society for Ecological Restoration (SER) defines ecological restoration as the process of assisting the recovery of an ecosystem that has been degraded, damaged or destroyed. This process includes any activity that has the goal of achieving substantial ecosystem recovery relative to an appropriate reference model, regardless of the time required to achieve recovery. Full recovery is defined as the state or condition whereby, following restoration, all key ecosystem attributes closely resemble those of the reference model. These attributes include absence of threats, species composition, community structure, physical conditions, ecosystem function and external exchanges (Gann *et al.* 2019). Peatland restoration should aim to return degraded peatlands to conditions in which ecosystem functions (e.g. carbon, energy and nutrient dynamics, decomposition of organic matter, biodiversity, production of biomass and water regulation) are as close as possible to natural conditions within the constraints of practicality (Clarke and Rieley 2019). It should be noted that the full restoration of cutover bog is clearly impossible due to the fact that large amounts of peat have been removed from the system (Wilson *et al.* 2007). However, where full restoration is not possible, an ecological restoration project or program should aspire to substantial recovery of the native biota and ecosystem functions (Gann *et al.* 2019) and restoration can be considered successful once the targets of the specific project are met.

Peatland restoration has evolved in the last number of decades to include a suite of management techniques aimed at speeding up the recovery process. Some of these were reviewed by Andersen *et al.* (2017) who noted a lack of robust, standardised monitoring schemes across restoration projects in Western Europe. The simplest restoration method, which has proved to be very effective on many sites, is to block any former drainage systems (Gonzalez *et al.* 2014; Mackin *et al.* 2017a; Thom *et al.* 2019). The purpose is to raise the water table in the drain and in adjacent bog in order to reduce run-off rates, and to create the hydrological conditions necessary for *Sphagnum* growth. Added measures include the active reintroduction of peatland diaspores (Gorham and Rochefort 2003; Hugron *et al.* 2020) and the uses of mulches to ameliorate the microclimate surrounding regenerating plants (Rochefort 2000). Others described by Price *et al.* (2003) include the provision of companion species, water pumping, surface reconfiguration, the establishment of buffer zones and the use of berms or terraces to retain water. Whilst water table dynamics are the principal drivers for ecological sustainability, vegetation cover—particularly the cover of *Sphagnum*—and total indicator species are often the main proxy indicators used for evaluating restoration success.

The vegetation of ombrotrophic peatlands is dominated by bryophytes from the genus *Sphagnum* (Robroek *et al.* 2009) and these play a pivotal role in their proper functioning and also in achieving restoration success (Similä *et al.* 2014). While there is considerable variation in the distribution and diversity of *Sphagnum* spp. on raised bogs, the vegetation on remaining intact high bog can be grouped into an 'ecotope' classification and mapping scheme (Kelly and Schouten 2002; Regan *et al.* 2020). Ecotopes are vegetation communities with similar characteristic water table depths, fluctuations and hydrochemistry (van der Schaff and Streefkerk 2002). They thereby can be used to classify the ecological quality of habitats and represent a hydro-sequence from dry to permanently saturated zones. Ecotopes can then be used effectively as a monitoring tool, as areas of ARB can be delineated and temporal mapping allows the natural or anthropogenic changes in the location and quality of vegetation/habitats to be measured (Regan *et al.* 2020).

A number of ecotopes have been classified for raised bogs in Ireland and a full description is available in Kelly and Schouten (2002). However, four primary ecotope types, marginal, submarginal, subcentral and central, are the most common and widely distributed. Central (the best quality ecotope) and subcentral are considered to be ARB, while the extent of DRB in Ireland is established using hydrological modelling techniques (Mackin *et al*. 2017b). DRB, is however, more likely to overlap with areas mapped as submarginal than marginal ecotope, the latter being more degraded and usually considered incapable of regenerating to ARB or DRB (NPWS 2018; Regan *et al*. 2020). The differentiation between ecotopes is broadly based on the percentage of *Sphagnum* cover (>40–50% cover of *Sphagnum* is generally indicative of ARB) and the presence of micro-topographical features, such as hummocks, hollows and pools, which are created by the differential growth of the mosses themselves (Rydin 1993). However, this classification scheme is applicable on the high bog only and such a concentric schema (grading from wet to dry ecotope types) of mapping does not apply to cutover bog as it is such a variable habitat that has formed as a result of historical anthropogenic impacts. The variability of the habitat is, in turn, determined by such factors as the frequency and extent of disturbance, hydrology, the depth of peat remaining and the nature of the peat and the underlying substratum (Fossitt 2000). Note the distinction between cutover raised bog, which is the focus of this study, and cutaway bog. Cutaway generally refers to areas where peat was industrially harvested, often leaving little (up to 50cm) or no peat layer remaining, while cutover generally refers to areas of that were domestically cut for peat and usually have greater and often more variable depths of peat remaining (O'Connell and Foss 1999).

Despite the heterogeneity of cutover bog, a habitat classification has recently been developed (Smith and Crowley 2020) that separates cutover into four habitat groups defined using the percentage cover of *Sphagnum*—Low *Sphagnum* (LS), Moderate *Sphagnum* (MS), High *Sphagnum* (HS) and bare peat (BP). These encompass sixteen habitat types that are defined using species composition. A methodology for assessing whether an area of High *Sphagnum* habitat corresponds with ARB was also developed based largely on the number of positive indicator species, and will be deployed by the national nature conservation agency— the National Parks and Wildlife Service (NPWS)—to gauge progress towards meeting national conservation targets (NPWS 2015, 2019). However, the NPWS (2019) recognise that the development of high-quality ARB with a well-developed micro-topography and diversity of indicator species can take a long time (50–100 years), but positive changes can be gauged much sooner with the development of embryonic ARB. Alderson *et al*. (2019) and Rochefort *et al*. (2003) report key indicator species establishing themselves on previously drained peat within the first five years of post-restoration. However, long-term restoration success needs to be assessed over several decades in order to establish whether the appropriate ecosystem structure, function, trophic organisation and biodiversity have been restored to a condition resembling the original peatland system (Gorham and Rochefort 2003).

Raised bog ecosystems that have been degraded as a result of drainage generally require engineering measures to restore the hydrological conditions necessary to support ARB. The presence and stability of *Sphagnum* spp. on raised bogs is largely dependent on the dynamics of the water table relative to the ground level and persistently high water tables are required (<0.15- m depth) (Regan *et al*. 2020). Similar hydrological regimes have been reported for peat-forming habitats on cutover peatlands (Renou-Wilson *et al*. 2018; Quinty and Rochefort 2003). Surface slope is a key factor in sustaining this high water table and shallow topographic gradients in the order of 0.3% are optimal to maintain ARB (van der Schaaf and Streefkerk 2002; Mackin *et al*. 2017b; Regan *et al*. 2020). This criterion is applied in raised bog restoration techniques by constructing berms in suitable areas such as relatively flat cutovers with a contributing flow from nearby high bog (Mackin *et al*. 2017a) in order to improve water retention. The depth to which *Sphagnum* can efficiently access water via capillary action is relatively shallow. A lowering of the water table by as little as 0.2m is sufficient to break the capillary water stream and reduce the percentage of capillary water by over 95% (Clymo and Hayward 1982). Even relatively modest surface drainage can thereby impact on the effectiveness of capillary action to supply sufficient water to maintain the health of the *Sphagnum* carpet. Conversely even relatively small increases in water table levels, which help maintain the water table close to the bog surface (<0.1m) will restore conditions for active *Sphagnum* growth. This criterion is applied in raised bog restoration engineering design, such as the placement of dams to impede water flow, to ensure that appropriate hydrological conditions are achieved (Regan *et al*. 2020).

The influence of restoration works on cutover raised bog ecology is understudied in Ireland and this knowledge gap impedes the development of methods that can be used to monitor the condition and recovery of cutover habitats following management interventions. Thus, the aim of this study was to, first, assess the vegetation changes that have occurred on an area of representative restored cutover bog in Ireland, using detailed vegetation surveys carried out before and after (7–13 years) restoration activities, and second, to use this data to determine whether the *Sphagnum*-rich vegetation that now occurs on parts of the cutover can be classed as ARB. The findings from this study have implications for cutover raised bog management and are discussed herein.

MATERIALS AND METHODS

SITE DESCRIPTION

This study was carried out at Killyconny Bog, a lowland raised bog located towards the eastern extent of ARB in Ireland (53°78′N, 6°97′W; Figure 1), and designated as a Special Area of Conservation (SAC) under the European Union (EU) Habitats Directive (Council Directive 92/43/EEC). The area experiences a temperate Atlantic climate with a mean annual (1981–2010) temperature and rainfall of 9.2 °C and 965mm, respectively (Walsh 2012). The bog is 185ha in extent, composed of 83ha of intact high bog with surrounding areas of cutover bog, scrub, reclaimed pasture and an area of developing birch woodland that was a former conifer plantation. The bog is underlain by clays and clayey limestone till (Kelly *et al.* 1995) and the underlying bedrock is mapped by the Geological Survey of Ireland (GSI) as Silurian calcareous red-mica greywacke.

The most recent monitoring survey of the high bog estimated the area of ARB to be 3.9ha, composed of 3.7ha of subcentral ecotope and 0.2ha of central ecotope (Fernandez *et al.* 2014) while the conservation target of ARB for the site is 13.2ha (NPWS 2018). This target is set using a hydrological modelling technique, which can quantify a raised bog's restoration potential (see NPWS 2018 for further details of the technique). From this modelling process, it is estimated that the maximum achievable target for ARB on the high bog is 8.7ha with an additional 4.5ha of ARB restorable on the cutover (NPWS 2018). The NPWS carried out restoration work on Killyconny Bog between 2006 and 2010. Hitherto, restoration of raised bogs in Ireland concentrated on drain blocking on the high bog to repair the hydrological regime and encourage expansion of ARB. At Killyconny, the NPWS undertook a number of experimental restoration measures (see Woodworth 2013) such as the grading of facebanks, the creation of a linear berm along the edge of part of the high bog and the installation of a solar powered pump to transfer water from artificial pools created on the cutover back onto the high bog. These measures are not assessed here and are generally considered to have met with limited success. The pump, for example, only operated when there was enough sunshine and this intermittent functioning led to repeated blockages and thus long periods of break-down. In any case, the water chemistry of the water being pumped back onto the high bog had not been analysed for its suitability and due to these factors the solar pump experiment was abandoned. In regard to the linear high bog berm, it is thought that the bog slopes where it was located were too steep (>3%), resulting in flow along the length of the bund and ultimately in a number of bund structural failures. However, conversely the construction of a berm along the western margin of the cutover bog was largely successful and this current research aims to give quantitative details of the outcomes. As well as the NPWS works, a section of the bog (Figure 2), which was planted with conifer plantations by the Irish forestry company *Coillte*, underwent restoration measures in 2004–08 under a LIFE-funded project (LIFE04 NAT/IE/000121). These works are not assessed here.

Approximately five kilometres of drains on the western cutover were blocked between 2006–10 with *c.* 140 peat and/or plastic dams (Figure 2) with dams installed at every 0.1m drop in elevation gradient (NPWS 2014). This was to ensure viable conditions for *Sphagnum* regeneration, where the water table must be maintained within 0.2m of the peat surface (Regan *et al.* 2020). In addition, a 1.7km barrier dam (berm) was installed along the western margin of the cutover bog (Figure 2). The berm is *c.* 0. 75m higher than the surface of the cutover, and an overflow pipe was installed at its southern end to prevent the development of high water levels that might damage the berm and/or impede *Sphagnum* regeneration. The pipe discharges into a deep marginal drain that separates the western cutover from adjacent agricultural pastureland, preventing any impacts on the agricultural land.

Killyconny bog is one of twelve sites undergoing restoration works as part of the EU funded LIFE project *The Living Bog* (LIFE14 NAT/IE/000032). As part of project, the western cutover at Killyconny was chosen to study the impact of the previous restoration measures (i.e. berm and drain blocking) on the regeneration of cutover bog ecology. This site is 26.9ha in extent, situated entirely on cutover bog in the western side of the SAC. Turf cutting ceased here in the late 1990s, but the residual effects of cutting and associated drainage continued to dry out the site.

TOPOGRAPHY

A 1m resolution Digital Terrain Model (DTM) was acquired for the site in May 2012. The DTM data has a stated vertical accuracy of +/-250mm on hard surfaces. The accuracy of the DTM on raised bog surface is likely to vary considerable depending on vegetation cover, with relatively high accuracy (+/- 250mm) anticipated in areas with low vegetation cover (such as bare peat areas) and lower accuracy in areas with increasing vegetation cover (such tall *Calluna* cover or regenerating woodland). From the DTM, it is evident that the cutover at Killyconny is relatively flat, albeit with considerable variation in microtopography. In order to generalise the topographic surface and reduce the confounding impact of microtopography on surface slopes across the study area the 1m resolution DTM was reprocessed to 20m resolution using the Neighbourhood toolbox within the Spatial Analyst extension of ArcMap v10.5.

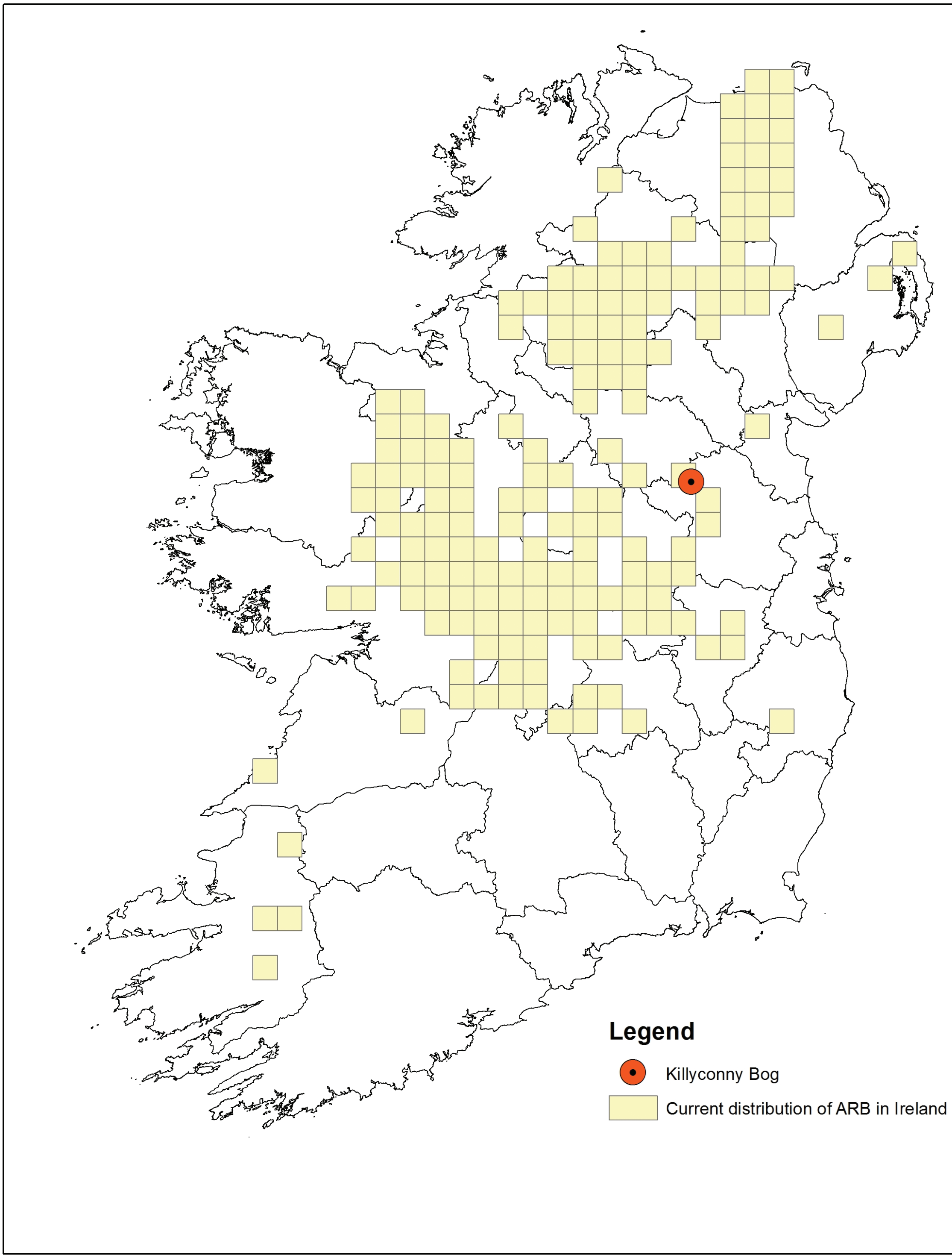

Fig. 1—Location of Killyconny Bog (SAC 000006) within the context of the current distribution of Active Raised Bog (ARB) (NPWS 2019) on the island of Ireland. There is no comprehensive estimate of the extent of ARB in Northern Ireland (NI) as the scientific authority do not accurately map or measure its (or Degraded Raised Bogs (DRB)) extent and indeed do not make a great distinction between ARB and DRB (Anon 2019). In contrast, the scientific authority in the Republic of Ireland has a survey protocol to identify ARB in the field and also a model-based methodology for mapping areas of DRB. Thus, the current distribution of ARB in NI would be an overestimation using the NPWS definition.

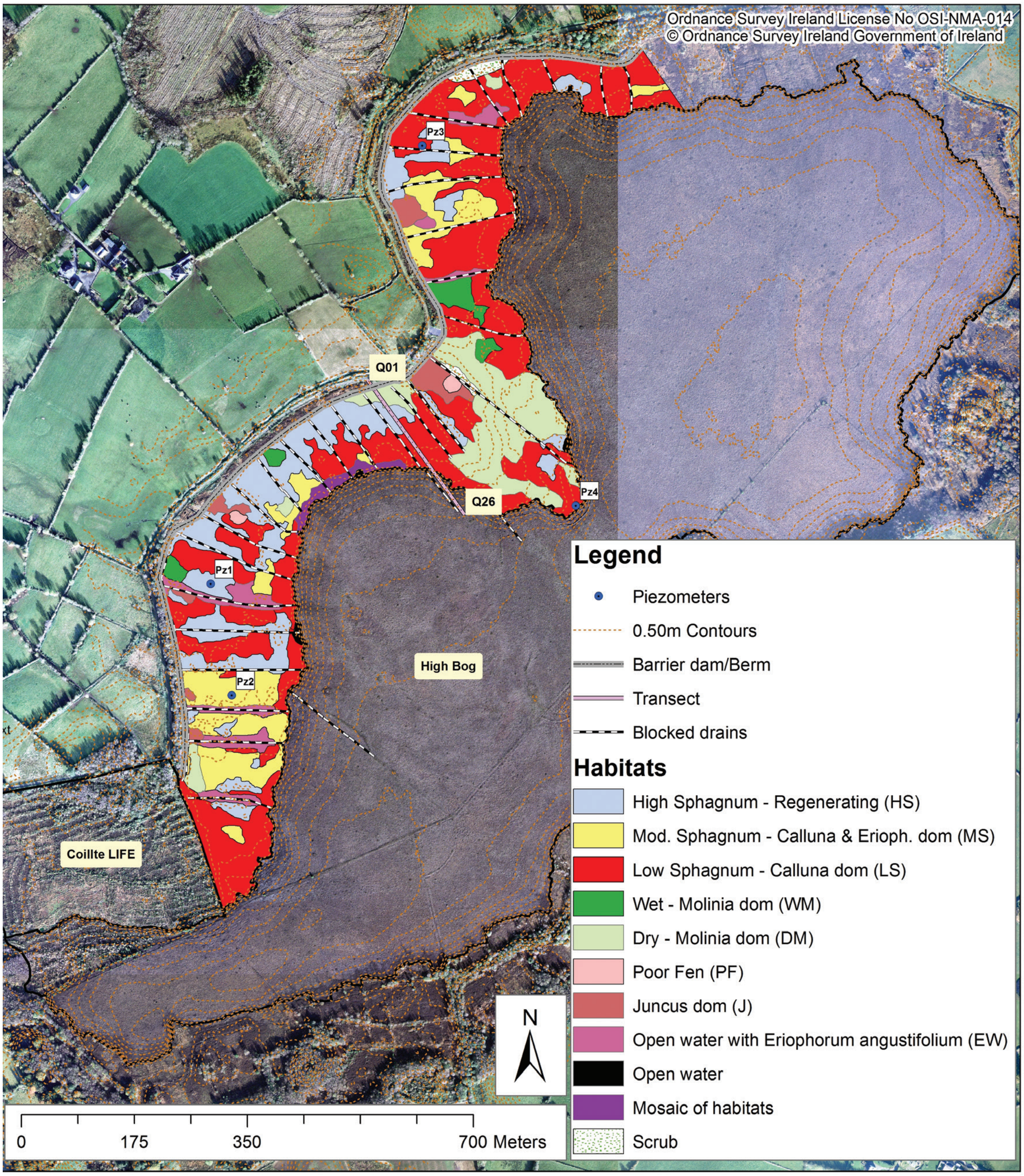

Fig. 2—Map of the vegetation types on the western cutover at Killyconny in 2017 between the barrier dam (berm) and the high bog.

FIELD SURVEYS

A baseline vegetation transect was established by Dwyer and Wann (2005) across the study site in October 2005. The transect ran SSE from peripheral drain at the edge of the SAC across an extensive area of cutover and high bog (Figure 2). It measured 255m in length with 25m^2 quadrats (5m × 5m) established every 10m, resulting in a total of 26 quadrats. Seventeen quadrats were on the cutover (Q1–17), seven were on the high bog (Q20–26), and two (Q18–19) partly on the high bog and partly on the cutover. In October 2018 the transect was resurveyed. At each quadrat, the 2005 and 2018 surveys recorded percentage cover of all vascular plant, bryophyte and lichen species, as well as percentage cover of bare peat and total *Sphagnum*. Nomenclature follows Stace (2019) for vascular plants, Blockeel and Hodgetts (2019) for bryophytes and Dobson (2018) for lichens. In 2018 quadrats Q1 and Q2 were located outside of the berm while Q3 was partially outside the berm.

In addition to the transect, Dwyer and Wann (2005) undertook a general survey of a 4.5ha section of the cutover in October 2005, which was representative of the cutover habitat conditions across the entire western cutover at the time. In 2017 and 2019, the vegetation in the 26.9ha of the western cutover was sampled following the Zurich-Montpellier method (Shimwell 1971; Mueller-Dombois and Ellenberg 1974). This involved taking a stratified random sampling approach where the site is first divided into vegetation 'compartments' based on their floristic similarities and differences. The vegetation compartments of the western cutover at Killyconny were mapped initially by an analysis of the most recent aerial photography (2012) from Ordnance Survey Ireland. Distinct vegetation patterns were identified on the aerial photograph and mapped using ArcMap v10.3. A field survey was then undertaken in September 2017, and nine vegetation types were recognised as follows:

1. Low *Sphagnum* (<25% cover) - *Calluna vulgaris* dominated (LS)
2. Moderate *Sphagnum* (25–50% cover) - *Calluna vulgaris* and *Eriophorum* spp. dominated (MS)
3. High *Sphagnum* (>50% cover) - Regenerating cutover (HS)
4. *Molinia caerulea* dominated and dry (DM)
5. *Molinia caerulea* dominated and wet (WM)
6. Poor fen (PF)
7. *Juncus* spp. dominated (J)
8. Dominated by open standing water and *Eriophorum angustifolium* (EW)
9. Scrub

The western cutover was subsequently surveyed in detail in October 2017, and pre-survey desktop boundaries were amended on the ground using a GeoExplorer handheld GPS minicomputer (Trimble Geo7x) with submetre accuracy. A minimum habitat area of 400m^2 was used (Smith *et al.* 2011). A number of relevés, located randomly, were recorded in each vegetation type (except scrub, which was not sampled) in September and October 2019. The relevé size in each vegetation type was 2m x 2m and at each relevé, the abundances of all vascular plant, bryophyte and lichen species were recorded using the Domin scale. In addition to plant species Domin scores, the total *Sphagnum* percentage cover and cover of bare peat were estimated.

HYDROLOGICAL MONITORING

Hydrological monitoring was carried out as part of the as part of *The Living Bog* project between November 2018 and October 2019. This involved installation of a network of piezometers across the high bog and cutover at Killyconny Bog, four of which are located within the study site (Figure 2). Each monitoring location consists of a 38mm internal diameter PVC water table piezometer with a 1.5m screened interval, installed in the upper layer of peat. Monthly measurements of depth to water table were carried out at each piezometer. Each piezometer was surveyed with a survey-grade GNSS unit (Trimble R8 (Trimble Inc, CA, USA)) to provide elevations for top of casing and ground surface (+/- 20mm accuracy), with all water levels reported relative to the surveyed ground surface.

DATA ANALYSIS

All statistical analyses were performed in the R statistical environment. Differences in vegetation composition between sampling years in the transect plots were tested using permutational multivariate analysis of variance (MANOVA) (Anderson 2001). This was implemented using the function 'adonis' in the package 'vegan' using the Bray-Curtis distance measure. Prior to analysis, the dispersion of plots from the year centroids was calculated using the function 'betadisper' in package 'vegan', and the hypothesis of homogeneity of dispersion (variance) was tested.

To determine if *Sphagnum* cover on the cutover and the high bog transect plots had increased from 2005 to 2018, one-sided paired sample Wilcox signed rank tests (Sokal and Rohlf, 1995) were used, implemented by the function 'wilcox.test'. Two-way ANOVA was used on square root transformed values to test differences in the number of positive indicators of ARB among survey years and high bog / cutover bog status, implemented by the function aov.

Non-metric multi-dimensional scaling (NMS) (Minchin 1987; Legendre and Legendre 1998), implemented using the function 'metaMDS' in package 'vegan', was used to investigate differences in transect vegetation among location and between years. A two-dimensional solution was sought using the Bray-Curtis distance measure. The minimum number of random starting configurations used was 50. Quadrat 1 was omitted from the NMS, as it was located adjacent to the access track and drain and contained several species not encountered in any other plot.

Additionally, a comparison is made with data from fifteen quadrats (4m x 4m) taken from ARB (eight from central ecotope and seven from sub-central ecotope) on high bog in 2016 across three (Ardagullion, Raheenmore and Mongan) raised bog sites that lie 35km, 55km, and 80km to the south-west of the study site. Data from these sites, together with that from Killyconny, were assessed in terms of the definition of ARB on cutover in Ireland devised by Smith and Crowley (2020). This definition states that for an area to be assessed as ARB it requires, in a $100m^2$ area, to have the eight species listed as constants of ARB, and a minimum of four of the additional fifteen species listed as positive indicators of ARB. The web application ERICA (Perrin 2020) was used to obtain the mean values for Ellenberg's indicator values for each quadrat, the reference values coming from Hill *et al*. (2004, 2007). These are environmental proxy scores for moisture, reaction/acidity and nitrogen/fertility. The Ellenberg value for a quadrat is the mean value of each species weighted by its abundance in the quadrat. Ellenberg values range from 1–9 with high scores for moisture indicating wetter conditions, for acidity indicating more basic conditions and for nitrogen indicating more fertile conditions.

RESULTS

TRANSECT

A summary of the quadrats analysed in 2005 and 2018 is provided in Table 1. In Table 1, Q1–Q3 are omitted as they were outside or partially outside of the zone of influence of the restoration works; Q18–Q19 were omitted as they were not wholly within either cutover or high bog. The vegetation composition of the transect plots between 2005 and 2018 was significantly different ($p = 0.001$), according to permutational MANOVA. When the analysis was restricted to the 14 cutover bog plots entirely within the berm (Q4–Q17) or the seven plots entirely on the high bog (Q20–Q26), vegetation composition between survey years remained significantly different ($p=0.001$ and $p=0.007$, respectively).

Figure 3 shows how *Sphagnum* cover has increased across the restored cutover (Q4–Q17) (Wilcox signed rank test $p=0.0005$). There has also been an increase in the *Sphagnum* cover on the adjacent high bog (Q20–Q26) (Wilcox signed rank test $P=0.016$). In 2005, no quadrat on the cutover had a *Sphagnum* cover of >1% and only five of the cutover quadrats (Q5–Q7 and Q15–Q16) had any *Sphagnum* recorded at all. Table 1 suggests that there may have been a decrease in the cover of bare peat, but differences were not significant for either cutover or high bog quadrats. The number of positive indicators of ARB on the high bog and the cutover was significantly higher in 2018 than 2005 (ANOVA $p<0.0001$); the number of positive ARB indicators (in both years combined) was also greater on the high bog than on the cutover (ANOVA $p<0.0001$).

Two convergent NMS solutions were found after 90 random starts. The stress of the final solution was 0.186. The first (horizontal) NMS axis appears to reflect a gradient from more ombrotrophic conditions on the right, where the high bog plots are clustered, to more nutrient-rich or at least flushed conditions that support such species as *Juncus effusus*, *Molinia caerulea*, *Kindbergia praelonga* and *Sphagnum fallax* (Figure 4). The second (vertical) axis clearly reflects change over the survey interval from drier and/or more disturbed conditions, indicated by such species as *Eriophorum angustifolium, Calluna vulgaris* and *Erica tetralix*, to more *Sphagnum*-rich vegetation. There is convergence in vegetation composition over time between the majority of high bog and cutover bog plots, which were clearly separate in 2005. The exception is a small number of cutover bog plots that support an increasing abundance of flush species, such as *Sphagnum fallax*.

VEGETATION SURVEY

Synoptic tables for eight of the nine vegetation types that were mapped on the western cutover at Killyconny are shown in Table 2 and described below. Additionally, a comparison is made with data from fifteen quadrats (4m x 4m) taken from ARB on three other raised bog sites. *Betula* scrub was mapped as covering 0.2ha of the cutover but not sampled while two additional categories, open water and mosaic of habitats, were mapped as covering 0.1ha and 0.4ha respectively. Table 3 provides data on *Sphagnum* and bare peat cover, species richness and environmental proxies (mean Ellenberg values) for each vegetation type.

Low *Sphagnum* (LS) was the most common vegetation type on the western cutover at Killyconny covering 11.9ha of the 26.9ha (44%). *Calluna vulgaris* dominated as an almost continuous cover often growing up to 1m in height with little or no *Sphagnum* underneath. Species typical of wet bogs were either absent, such as *Drosera* species, *Sphagnum medium*, *S. papillosum* and *Vaccinium oxycoccos*, or sparse, such as *Eriophorum vaginatum*, in this vegetation type and this is reflected in the low mean Ellenberg indicator value (Table 3) for moisture (6.5 ± 0.1). The peat surface was firm underfoot and *Hypnum jutlandicum* was the dominant bryophyte. Patches of bare peat and *Campylopus introflexus* were also often present.

High *Sphagnum* (HS) was the second most common vegetation type, covering 5.0ha (19%) of the study area. *Eriophorum vaginatum* and various *Sphagnum* species, especially *S. papillosum*, were the dominant species, accompanied by a range of other typical raised bog species. Drier, heath species such as *Calluna vulgaris* and *Hypnum jutlandicum* were markedly less abundant. In comparison to the quadrats from ARB on the high bog, however, there were a number of notable absences such as *Andromeda polifolia*, *Sphagnum austinii*, *S. beothuk*, *Narthecium ossifragum*, *Drosera anglica, Cladonia uncialis, Cladipodiella fluitans* and *Menyanthes trifoliata*. Although *Narthecium ossifragum*, and *Andromeda polifolia* were noted on

Table 1—Floristic comparison of the 2005 and 2018 quadrats along the monitoring transect divided according to quadrat location (cutover bog and high bog) and survey year. Also shown for comparison are 15 ARB quadrats from three other raised bog sites. Roman numerals represent the frequency of a species within a group: I = < 20%; II = 21–40%; III = 41–60%; IV = 61–80%; V = >80%. Species that do not have a frequency higher than I in any habitat type have been omitted. For transect quadrats, numbers in parentheses represent the mean percentage cover values ± Standard Error. For ARB comparison quadrats, numbers in parentheses are Domin scale ranges. Species in bold are those considered to be positive indicator species for ARB in Ireland and are listed in Smith and Crowley (2020). Transect quadrat size was 25m^2 and ARB comparison quadrat size was 16m^2.

	Cutover 2005	*Cutover 2018*	*High Bog 2005*	*High Bog 2018*	*ARB*
Number of quadrats	14	14	7	7	15
Sphagnum (Mean % cover)	0.3 ± 0.1	28.2 ± 4.9	3.5 ± 1.5	15.3 ± 2.9	69.7 ± 3.7
Bare peat (Mean % cover)	11.3 ± 4.3	2.0 ± 0.8	3.0 ± 1.4	2.3 ± 1.3	0
Mean (±SE) no. of positive indicators species of ARB (max possible score = 23)	2.9 ± 0.2	6.7 ± 0.5	6.7 ± 0.6	9.4 ± 0.3	14.1 ± 0.5
Andromeda polifolia		I (0.1 ± 0.1)	V (1.3 ± 0.6)	V (0.6 ± 0.1)	V (1–3)
Aulacomnium palustre		I (0.1 ± 0.1)	I (0.1 ± 0.1)	III (0.4 ± 0.2)	I (1–4)
Betula pubescens	I (0.1 ± 0.1)	II (0.2 ± 0.1)			I (1–2)
Calluna vulgaris	V (19.4 ± 3.7)	V (43.6 ± 7.7)	V (48.6 ± 9.1)	V (55.0 ± 3.9)	V (3–6)
Calypogeia fissa		IV (0.8 ± 0.2)			
Campylopus flexuosus		II (0.1 ± 0.1)		I (0.1 ± 0.1)	
Campylopus introflexus	II (0.5 ± 0.4)	III (0.7 ± 0.2)	I (0.1 ± 0.1)	V (0.7 ± 0.1)	I (1–2)
Carex panicea					II (1–4)
Cephalozia connivens		II (0.2 ± 0.1)			I (1–1)
Cladonia crispata			II (0.1 ± 0.1)	III (0.4 ± 0.2)	
Cladonia floerkeana	I (0.1 ± 0.1)	II (0.2 ± 0.1)	IV (0.4 ± 0.1)	II (0.2 ± 0.1)	
Cladonia portentosa		I (0.1 ± 0.1)	IV (0.6 ± 0.1)	V (6.0 ± 0.7)	V (1–6)
Cladonia uncialis					IV (1–2)
Cladopdiella fluitans					II (1–2)
Drosera rotundifolia	III (0.3 ± 0.1)	II 0.2 ± 0.1)	I (0.1 ± 0.1)	I (0.1 ± 0.1)	V (1–3)
Drosera anglica					IV (1–2)
Dryopteris carthusiana	I (0.1 ± 0.1)	II (0.2 ± 0.1)			
Erica tetralix	V (4.5 ± 0.8)	V (2.6 ± 0.5)	V (21.4 ± 6.7)	V (19.3 ± 1.3)	V (2–5)
Eriophorum angustifolium	V (36.1 ± 7.7)	V (8.4 ± 1.4)	V (1.3 ± 0.6)	V (1.1 ± 0.1)	V (2–5)
Eriophorum vaginatum	V (20.1 ± 5.1)	V (27.9 ± 5.4)	II (0.2 ± 0.1)	V (4.1 ± 1.5)	V (3–5)
Hypnum jutlandicum	I (0.4 ± 0.4)	V (8.3 ± 3.6)	III (0.4 ± 0.2)	V (3.0 ± 0.4)	V (2–4)
Juncus effusus	I (0.1 ± 0.1)	II (0.2 ± 0.1)			
Kindbergia praelonga		II (0.2 ± 0.1)			
Kurzia pauciflora		II (0.1 ± 0.1)		II (0.1 ± 0.1)	I (1–2)
Menyanthes trifoliata					II (1–5)

Table 1 (continued)—Floristic comparison of the 2005 and 2018 quadrats along the monitoring transect divided according to quadrat location (cutover bog and high bog) and survey year. Also shown for comparison are 15 ARB quadrats from three other raised bog sites. Roman numerals represent the frequency of a species within a group: I = < 20%; II = 21-40%; III = 41-60%; IV = 61-80%; V = >80%. Species that do not have a frequency higher than I in any habitat type have been omitted. For transect quadrats, numbers in parentheses represent the mean percentage cover values ± Standard Error. For ARB comparison quadrats, numbers in parentheses are Domin scale ranges. Species in bold are those considered to be positive indicator species for ARB in Ireland and are listed in Smith and Crowley (2020). Transect quadrat size was 25m^2 and ARB comparison quadrat size was 16m^2.

	Cutover 2005	*Cutover 2018*	*High Bog 2005*	*High Bog 2018*	*ARB*
Molinia caerulea	V (13.7 ± 5.8)	V (14.4 ± 5.8)			I (3)
Narthecium ossifragum		I (0.1 ± 0.1)	V (15.1 ± 3.5)	V (9.1 ± 2.4)	V (2–5)
Odontoschisma sphagni		III (0.5 ± 0.1)	II (0.1 ± 0.1)	V (1.1 ± 0.3)	V (1–3)
Polytrichum strictum		I (0.1 ± 0.1)		III (0.4 ± 0.2)	I (1–2)
Rhynchospora alba	I (0.1 ± 0.1)	I (0.2 ± 0.1)	IV (2.4 ± 0.9)	II (0.2 ± 0.1)	V (3–5)
Riccardia chamaedryfolia		II (0.1 ± 0.1)			
Sphagnum austinii					II (1–4)
Sphagnum beothuk					II (2–4)
Sphagnum capillifolium		V (4.1 ± 1.1)	IV (1.1 ± 0.7)	V (6.0 ± 1.9)	V (4–7)
Sphagnum cuspidatum		III (0.9 ± 0.4)			V (1–8)
Sphagnum denticulatum	I (0.1 ± 0.1)	II (1.8 ± 0.9)			
Sphagnum medium		IV (4.9 ± 1.8)		III (0.5 ± 0.2)	III (2–7)
Sphagnum palustre		V (5.6 ± 1.8)			
Sphagnum papillosum	I (0.1 ± 0.1)	V (7.2 ± 2.1)	I (0.1 ± 0.1)	V (0.8 ± 0.1)	V (3–7)
Sphagnum subnitens	II (0.1 ± 0.1)	IV (2.0 ± 0.5)	V (1.2 ± 0.6)	V (4.7 ± 1.2)	IV (1–4)
Sphagnum tenellum	I (0.1 ± 0.1)	III (0.7 ± 0.4)	IV (1.2 ± 0.6)	V (3.6 ± 0.7)	V (2–4)
Trichophorum germanicum	I (0.4 ± 0.4)	I (0.1 ± 0.1)	V (3.8 ± 1.3)	V (3.7 ± 0.6)	III (1–3)
Vaccinium oxycoccos					IV (1–2)

parts of the cutover (outside of relevés), none of the others were. The vegetation of the HS relevés was significantly different from the ARB relevés from the high bog (P = 0.001), according to permutational MANOVA, and HS would not qualify as ARB using the criteria developed by Smith and Crowley (2020) due to an insufficient number of positive indicators being present. A minimum of twelve positive indicator species within 100m^2 need to be present for cutover habitat to be considered as ARB (Smith and Crowley 2020), and only nine such species were recorded in the five 4m^2 relevés combined from this vegetation type. A further three species were recorded in adjacent vegetation types, however, possibly indicating that overall, the cutover is on a trajectory towards ARB.

Moderate *Sphagnum* (MS) was intermediate between the LS and the HS types and covered 13% of the cutover. *Calluna vulgaris* and *Eriophorum vaginatum* were typically the most abundant vascular plants, while *Hypnum jutlandicum*, *Sphagnum capillifolium* and *S. papillosum* were the principal bryophytes. Interestingly, this vegetation type supported some species also found in ARB on the high bog, but not in HS, such as the indicator species *Cladonia portentosa* and *Vaccinium oxycoccos* while the *Sphagnum subnitens* was more common in MS than HS. Moderate *Sphagnum* had a mean of 6.0 ± 0.3 positive

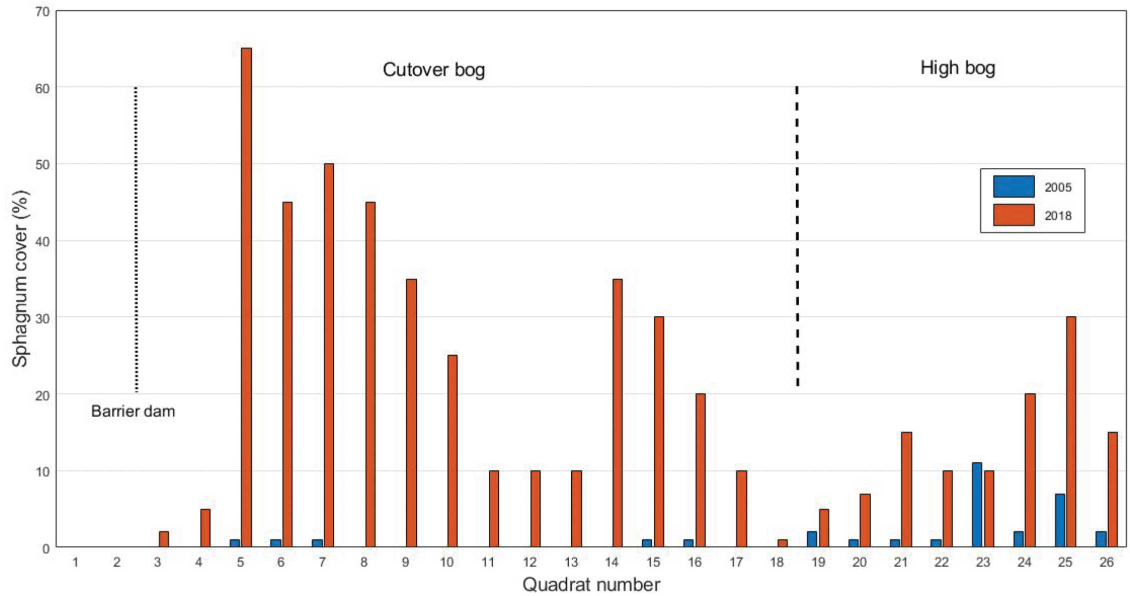

Fig. 3—Percentage *Sphagnum* cover per quadrat in 2005 and 2018.

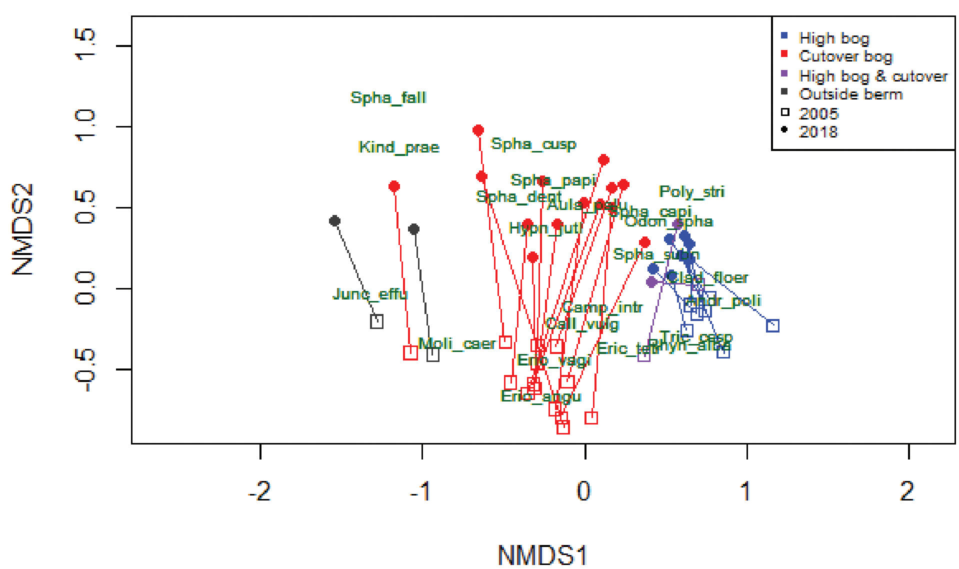

Fig. 4—NMS ordination of the transect plots. Final stress = 0.186. Lines connect the same plot surveyed in 2005 and 2018. Abbreviations for the subset of species displayed: Andr_poli = *Andromeda polifolia*, Aula_palu = *Aulacomnium palustre*, Call_vulg = *Calluna vulgaris*, Camp_intr = *Campylopus introflexus*, Clad_floe = *Cladonia floerkeana*, Eric_tetr = *Erica tetralix*, Erio_angu = *Eriophorum angustifolium*, Erio_vagi = *Eriophorum vaginatum*, Hypn_jutl = *Hypnum jutlandicum*, Junc_effu = *Juncus effusus*, Kind_prae = *Kindbergia praelonga*, Moli_caer = *Molinia caerulea*, Odon_spha = *Odontoschisma sphagni*, Poly_stri = *Polytrichum strictum*, Rhyn_alba = *Rhynchospora alba*, Spha_capi = *Sphagnum capillifolium* ssp *rubellum*, Spha_cusp = *Sphagnum cuspidatum*, Spha_dent = *Sphagnum denticulatum*, Spha_fall = *Sphagnum fallax*, Spha_papi = *Sphagnum papillosum*, Spha_subn = *Sphagnum subnitens*, Tric_cesp = *Trichophorum germanicum*.

ARB indicators per relevé compared to 5.6 ± 1.1 in HS. Nonetheless, Ellenberg values suggest that HS is closer to ARB conditions than MS with the moisture values for MS (6.9 ± 0.1) indicating that the areas are drier than typical ARB (7.5 ± 0.2) while HS (7.9 ± 0.1) is slightly wetter than typical ARB.

All other vegetation types studied (comprising 22% of the cutover) had raised pH level as indicated

Table 2—Floristic comparison of eight of the nine vegetation types recognised on the western cutover at Killyconny. Also shown are 15 quadrats from typical ARB. Roman numerals represent the frequency of a species within a group: I = < 20%; II = 21–40%; III = 41–60%; IV = 61–80%; V = >80%. Numbers in parentheses represent the range of Domin cover/abundance values. Species that do not have a frequency higher than I or do not occur in more than one relevé in any vegetation type have been omitted. Species in bold are those considered to be positive indicator species for ARB in Ireland and are listed in Smith and Crowley (2020). Quadrats recorded from the ARB comparison sites were 16m², whereas those from the cutover bog at Killyconny were 4m².

Vegetation type	*HS*	*MS*	*LS*	*DM*	*WM*	*PF*	*EW*	*J*	*ARB*
n	*5*	*5*	*4*	*6*	*1*	*3*	*2*	*4*	*15*
Calluna vulgaris	IV(2–4)	V(6–8)	V(7–9)	V(2–6)	V(5)	II(3)	III(1)	III(2–4)	V(3–6)
Erica tetralix	V(3–4)	V(3–4)	V(1–4)	II(1–2)	V(3)				V(2–5)
Eriophorum angustifolium	III(2–3)	III(1–2)	V(2–3)		V(3)	IV(1–2)	V(10)		V(2–5)
Eriophorum vaginatum	V(6–9)	V(5–8)	V(2–4)	V(3–5)	V(5)	II(2)			V(3–5)
Sphagnum capillifolium	V(2–4)	V(3–6)	II(4)	II(1–3)	V(2)	II(1)			V(4–7)
Hypnum jutlandicum	II(2–3)	V(4–6)	IV(4–8)	V(3–5)	V(4)		III(1)	IV(2–3)	V(2–4)
Sphagnum cuspidatum	III(4–5)	III(1–3)	II(2)		V(4)	II(3)			V(1–8)
Narthecium ossifragum									V(2–5)
Andromeda polifolia									V(1–3)
Rhynchospora alba	I(4)	I(4)	II(1)						V(3–5)
Drosera anglica									IV(1–2)
Cladonia uncialis									IV(1–2)
Sphagnum beothuk									II(2–4)
Sphagnum austinii									II(1–4)
Menyanthes trifoliata									II(1–5)
Carex panicea									II(1–4)
Cladopodiella fluitans									II(1–2)
Odontoschisma denudatum									II(1–2)
Dicranum scoparium		I(1)							II(1)
Sphagnum papillosum	IV(6–8)	V(2–4)							V(3–7)
Drosera rotundifolia	III(1)	I(1)							V(1–3)
Sphagnum medium	III(3–5)								III(2–7)
Riccardia sp	II(1)						III(1)		II(1–3)
Vaccinium oxycoccos		I(2)					III(2)		IV(1–2)

Table 2 (continued)—Floristic comparison of eight of the nine vegetation types recognised on the western cutover at Killyconny. Also shown are 15 quadrats from typical ARB. Roman numerals represent the frequency of a species within a group: I = < 20%; II = 21–40%; III = 41–60%; IV = 61–80%; V = >80%. Numbers in parentheses represent the range of Domin cover/abundance values. Species that do not have a frequency higher than I or do not occur in more than one relevé in any vegetation type have been omitted. Species in bold are those considered to be positive indicator species for ARB in Ireland and are listed in Smith and Crowley (2020). Quadrats recorded from the ARB comparison sites were 16m^2, whereas those from the cutover bog at Killyconny were 4m^2.

Vegetation type	*HS*	*MS*	*LS*	*DM*	*WM*	*PF*	*EW*	*J*	*ARB*
n	*5*	*5*	*4*	*6*	*1*	*3*	*2*	*4*	*15*
Sphagnum squarrosum				I(1)			III(1)		
Odontoschisma sphagni	I(2)	V(1–2)	III(1–2)						V(1–3)
Sphagnum tenellum		IV(1–3)	II(3)						V(2–4)
Cladonia portentosa		III(1–5)							V(1–6)
Sphagnum subnitens	I(1)	III(1–2)	II(2)						IV(1–4)
Trichophorum germanicum		II(1)	II(2)						III(1–3)
Calypogeia fissa	I(2)	IV(1–3)	III(2)	IV(1–3)		II(1)	III(1)	III(1–2)	
Polytrichum strictum	I(1)	II(1)		II(3–4)					I(1–2)
Campylopus introflexus	I(2)	II(1)	IV(1)	I(5)					I(1)
Cephalozia connivens	II(1)	I(1)	III(1–2)						I(1)
Kurzia pauciflora		I(1)	II(2)						I(1–2)
Molinia caerulea	III(1–3)	IV(2–4)	V(1–5)	V(6–9)	V(6)	V(4)	III(4)	V(5)	I(3)
Sphagnum palustre	II(2–4)		III(2–3)	IV(3–4)	V(7)	V(1–7)		II(5)	
Potentila erecta			II(2)	V(1–3)	V(2)			IV(2–4)	
Aulacomnium palustre				III(1–3)	V(1)			II(1)	I(1–4)
Cephaloziella sp		I(1)	II(1)	III(1–2)					
Juncus effusus				III(2–3)		V(8–9)		V(6–9)	
Kindbergia praelonga			II(1)	III(1–2)		V(3)	III(2)	IV(3–5)	
Rhytidiadelphus squarrosus				II(2–3)				II(1)	
Sphagnum fallax					V(2)	IV(4)			
Dryopteris carthusiana	I(1)			I(3)		IV(1)	III(1)	IV(1–3)	
Polytrichum commune				II(2–3)		IV(1–4)		IV(3)	
Agrostis canina				II(3–5)		IV(4–5)		III(5–6)	
Juncus acutiflorus						II(4)		II(5)	
Rumex acetosa						II(2)		II(3)	
Carex rostrata						II(2)		II(1)	

Table 2 (continued)—Floristic comparison of eight of the nine vegetation types recognised on the western cutover at Killyconny. Also shown are 15 quadrats from typical ARB. Roman numerals represent the frequency of a species within a group: I = < 20%; II = 21–40%; III = 41–60%; IV = 61–80%; V = >80%. Numbers in parentheses represent the range of Domin cover/abundance values. Species that do not have a frequency higher than I or do not occur in more than one relevé in any vegetation type have been omitted. Species in bold are those considered to be positive indicator species for ARB in Ireland and are listed in Smith and Crowley (2020). Quadrats recorded from the ARB comparison sites were 16m², whereas those from the cutover bog at Killyconny were 4m².

Vegetation type	*HS*	*MS*	*LS*	*DM*	*WM*	*PF*	*EW*	*J*	*ARB*
n	*5*	*5*	*4*	*6*	*1*	*3*	*2*	*4*	*15*
Anthoxanthum odoratum				I(1)		II(3)			
Galium palustre						II(4)			
Chamerion angustifolium						II(2)			
Holcus lanatus						II(2)			
Betula pubescens	I(3)			I(1)				III(1-5)	I(1-2)
Sphagnum fimbriatum								III(3-4)	
Brachythecium rutabellum			II(2)					III(1-2)	
Lophocolea bidentata				I(1)				III(1-3)	
Rubus fruticosus								II(3)	
Pteridium aquilinum								II(1)	

by the Ellenberg values for acidity. *Molinia caerulea*, which is largely absent from ARB, was a frequent species across most of the cutover bog in the study area, being a constant (except for the category dominated by open standing water and *Eriophorum angustifolium* (EW)) in the remaining vegetation types. In *Molinia caerulea* dominated and dry (DM), which covered 12% of the cutover, it was particularly abundant. *Potentilla erecta*, *Eriophorum vaginatum*, *Calluna vulgaris* and *Hypnum jutlandicum* were also constant species. *Sphagnum* cover was quite low, with the flush species *S. palustre* most frequent. *Sphagnum* cover was higher in *Molinia caerulea* dominated and wet (WM), comprising *S. palustre, S. cuspidatum, S. capillifolium* ssp. *rubellum* and *S. fallax*.

In contrast with the ombrotrophic vegetation types, the Ellenberg values for nitrogen (Table 3) in Poor fen (PF) and *Juncus* spp. dominated (J) indicate greater availability of nutrients in groundwater or moving surface water. Both types were characterised by abundant *Juncus effusus* and frequent *Molinia*. Poor fen supported a number of typical bog species in small quantities, in addition to a moderate cover of *Sphagnum palustre* and *S. fallax*. Although *Betula pubescens* was recorded sparingly within the vegetation type, it was not recorded within any of the relevés. *Juncus* spp. dominated was similar, but with lower *Sphagnum* cover, fewer bog species and more species typical of scrub or woodland.

The category dominated by open standing water and *Eriophorum angustifolium* (EW) was largely confined to the areas in and around blocked drains. This comprised species-poor swards of *Eriophorum angustifolium* emergent from flooded cutover bog.

In 2005, the vegetation of the western cutover was very different to that found during the 2017 and 2019 surveys. Dwyer and Wann (2005) stated that the cutover was dominated by bare peat with frequent *Calluna vulgaris* and made no mention of *Sphagnum* in their general description of the area. They also indicated that wetter depressions were dominated by *Narthecium ossifragum* and that primary colonisers of bare peat substrates such as *Eriophorum angustifolium*, the green alga *Zygogonium ericetorum*, the moss *Campylopus introflexus*, and the lichen *Cladonia floerkeana*, occurred at high cover values. In comparison with 2005, there were no significant areas of bare peat recorded in 2017/19. *Narthecium ossifragum* stands are no longer present, and this species

Table 3—Mean species richness (±SE), percent cover (±SE) of *Sphagnum* and bare peat and environmental proxies (mean Ellenberg values ±SE), in eight of the nine vegetation types recognised on the western cutover at Killyconny. Also shown are values from 15 quadrats from typical ARB. Quadrats recorded from the ARB comparison sites were 16m^2, whereas those from the cutover at Killyconny were 4m^2.

Vegetation type	HS	MS	LS	DM	WM	PF	EW	J	ARB
N	*5*	*5*	*4*	*6*	*1*	*3*	*2*	*4*	*15*
Area (ha)	5.0	3.4	11.9	3.1	0.6	0.1	1.2	0.7	N/A
Area (% of study site)	19	13	44	12	2	0	5	3	N/A
Mean (±SE) no. of species/relevé	13.2 ± 1.6	12.2 ± 0.8	10.8 ± 0.5	10.2 ± 0.6	17.0	11.0 ± 2.3	9.0 ± 1.0	12.0 ± 1.1	23.8 ± 0.8
Mean (±SE) no. of positive indicator species of ARB/relevé	5.6 ± 1.1	6.0 ± 0.3	3.3 ± 0.8	1.8 ± 0.3	5	1.7 ± 0.7	1.5 ± 0.5	0.3 ± 0.3	14.1 ± 0.5
Mean (±SE) *Sphagnum* cover	55.0 ± 10.4	21.0 ± 6.2	3.9 ± 3.7	3.5 ± 1.6	50	27.3 ± 8.2	1.0 ± 0.5	5.5 ± 4.9	69.7±3.7
Mean (±SE) bare peat cover (%)	0	0.4 ± 0.4	6.3 ± 6.3	0	0	0	0	0	0
Moisture	7.9 ± 0.1	6.9 ± 0.1	6.5 ± 0.1	7.1 ± 0.2	7.7	7.7 ± 0.1	8.8 ± 2.2	6.7 ± 0.2	7.5 ± 0.2
Acidity	1.8 ± 0.1	1.9 ± 0.1	2.1 ± 0	2.5 ± 0.1	2.5	3.3 ± 0.2	3.8 ± 1.0	3.8 ± 0.4	1.7 ± 0
Nitrogen	1.2 ± 0.1	1.5 ± 0.1	1.7 ± 0.1	1.8 ± 0.1	1.8	3.0 ± 0.2	1.2 ± 0.3	3.2 ± 0.3	1.2 ± 0.1

has become quite rare. *Calluna*, described in 2005 as 'frequent', has increased in abundance to dominate most drier areas, while *Molinia* became dominant in others, whereas previously it was largely restricted to drain margins.

TOPOGRAPHY

The generalised surface slope map (Figure 5) indicates that a large proportion of the study area has favourable topographic conditions for peat-formation (shallow topographic gradients of ≤0.3% as stated by Mackin *et al*. 2017b and Regan *et al*. 2020). These areas are considered the most likely to rewet through standard restoration techniques such as drain blocking and does not consider the impact of the barrier dam. Therefore, surface slope alone appears to be insufficient to explain the areas where regeneration of peat-forming conditions has occurred, with pockets of vegetation type HS occurring in areas with local surface slopes in excess of 1% and equally areas of slopes ≤0.3% that are not peat-forming. Nevertheless, there is demonstrable correspondence between surface slope and the probability of encountering vegetation type HS. Figure 6 indicates the relative frequency of surface slopes for each of the vegetation types HS, MS and LS. To eliminate the effect of the differences in total area covered by each vegetation type, the data was standardised by dividing the area of each slope class for each vegetation type by the total area of each vegetation type (giving areas for each slope class in ha/ha). The standardised area was then summed across all three vegetation types for each slope class, and the percentage of each vegetation type making up each slope class calculated as indicated in Figure 6. This illustrates the correspondence with slope, with greater probability of encountering vegetation type HS in areas with shallower surface slopes compared to MS and then LS. There is a clear pattern with vegetation type HS the most dominant vegetation type in areas of shallow surface slope and becoming less dominant as slope class increases, with vegetation type LS becoming most dominant when the slope exceeds 1%. MS increases as slope increases up to slope class 0.7%-1.0% (where it is most dominant), before being exceeded in dominance by LS in slope class ≥1%. It is also notable that areas of very gentle surface slope (≤0.3%) that occur within areas mapped as vegetation type HS tend to occur towards the centre of this vegetation type, with steeper slopes typically occurring towards the boundary between vegetation type HS and other vegetation types with lower *Sphagnum* cover (Figure 5).

Delineation of flow paths using the Hydrology Tools within the Spatial Analyst of ArcMap v10.5 also reveals correspondence between increasing contributing catchment area and occurrence

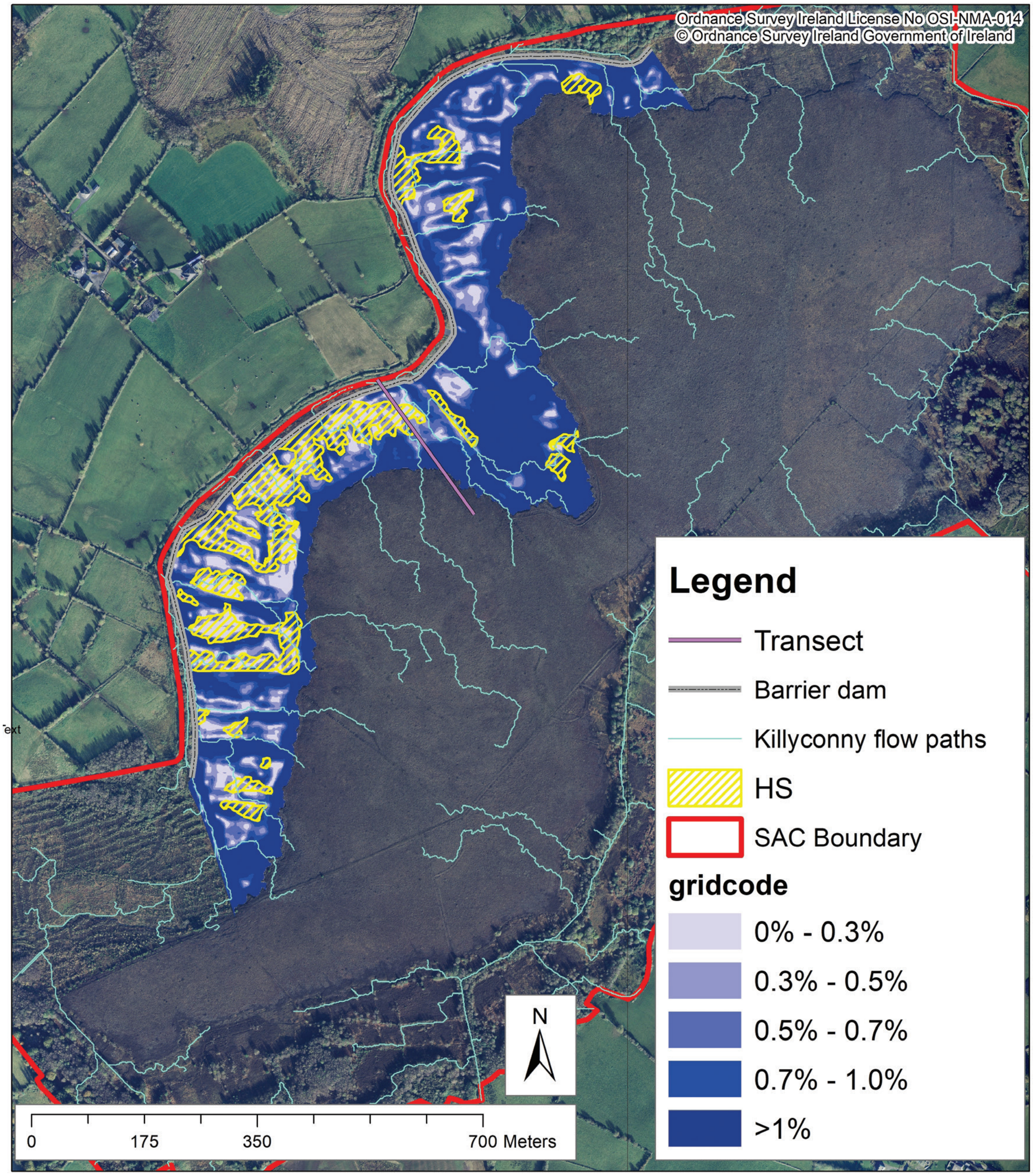

Fig. 5—Generalised surface slope map indicating that a large proportion of the study area has favourable topographic conditions for peat-formation (shallow topographic gradients of ≤0.3%).

of vegetation type HS (Figure 5) These simulated flow paths utilise the D8 flow direction algorithm (O'Callaghan and Mark 1984), which predicts flow from cell to cell on the basis that flow will continue to the lowest of the eight surrounding cells. In almost all instances the areas mapped as vegetation type HS have a minimum contributing catchment area of ≥5,000m^2. In addition to gentle surface slope, vegetation type HS appears to have occurred within depressions, although the extent of the mapped HS areas has extended beyond the edge of the defined depressions. This suggests that *Sphagnum* recovery may begin within enclosed hollows before spreading beyond the depression, primarily across areas of very gentle surface slope (≤0.3%) before advancing across slightly steeper slopes.

Examination of the topography of the cutover at Killyconny reveals close correlation between variations in elevation and areas mapped as vegetation type HS. Generation of contours at 25cm

Fig. 6—Relative frequency of surface slopes for the vegetation types HS, MS and LS.

intervals using the generalised 20m resolution DTM illustrates the close correspondence between 25cm contour intervals and vegetation mapping boundaries. As illustrated by the topographic profile (corresponding to the transect established by Dwyer and Wann (2005)) presented in Figure 7 there is close correspondence between the boundary of the HS vegetation type and the LS vegetation type at the 110.25mOD contour interval. At the start of the transect (close to the marginal berm) the topography is elevated slightly above the 110.25mOD contour interval (from transect length 10m–45m) and the area is mapped as vegetation type DM. In Figure 3, it can be seen that the quadrats along this section all had <10% cover of *Sphagnum*. The elevation then drops to below 110.25mOD and this corresponds very closely to the boundary of where vegetation type HS begins to be mapped (45m - 85m). The quadrats here had the highest *Sphagnum* cover along the transect length (all being >40%). The topography then rises above 110.25mOD further south-east and this again corresponds to vegetation type LS (until *c.* 180m where the high bog begins). The quadrats here mostly had a *Sphagnum* cover of 10–30%. This highlights that the narrow band of vegetation type HS is associated with a very slight depression in the topography and the extremely fine margins in the influence of topography on vegetation type.

HYDROLOGICAL DATA

Hydrological monitoring from November 2018 to October 2019 indicates that the water level is typically +/-15cm of the ground surface at each of the monitoring locations (note: piezometers become inaccessible when water levels exceed 15cm above ground surface, piezometers can be observed from a distance and 15cm markings were observed to be exceeded). Two of the piezometers are located within vegetation type LS (piezometer 3 and 4), one is located within vegetation type MS (piezometer 2) and one within vegetation type HS (piezometer 1), with a hydrograph for the monitoring period provided in Figure 8. Although monthly manual measurements may miss extremes in water levels, the data collected over the monitoring period indicates that the water level is above ground level at piezometer 1 (HS) at all times, despite being located on relatively flat ground outside of any depression. Similarly, the water level at piezometer 2 (MS) remains above ground throughout most of the year, only dropping below ground level during two monitoring visits. In contrast, water levels at piezometer 3 (LS) are below ground level throughout most of the year, rising above ground level (+4cm) during one monitoring visit. Similarly, at piezometer 4 water levels remain below ground surface throughout the entire year.

Although the data collected is limited in spatial and temporal extent, it illustrates how water levels vary relative to each other and shows correspondence between water level and vegetation type. The highest and most stable water levels are associated with vegetation type HS, relatively high water levels have been recorded within vegetation type MS although there is greater fluctuation than within HS, while the lowest water levels are recorded within

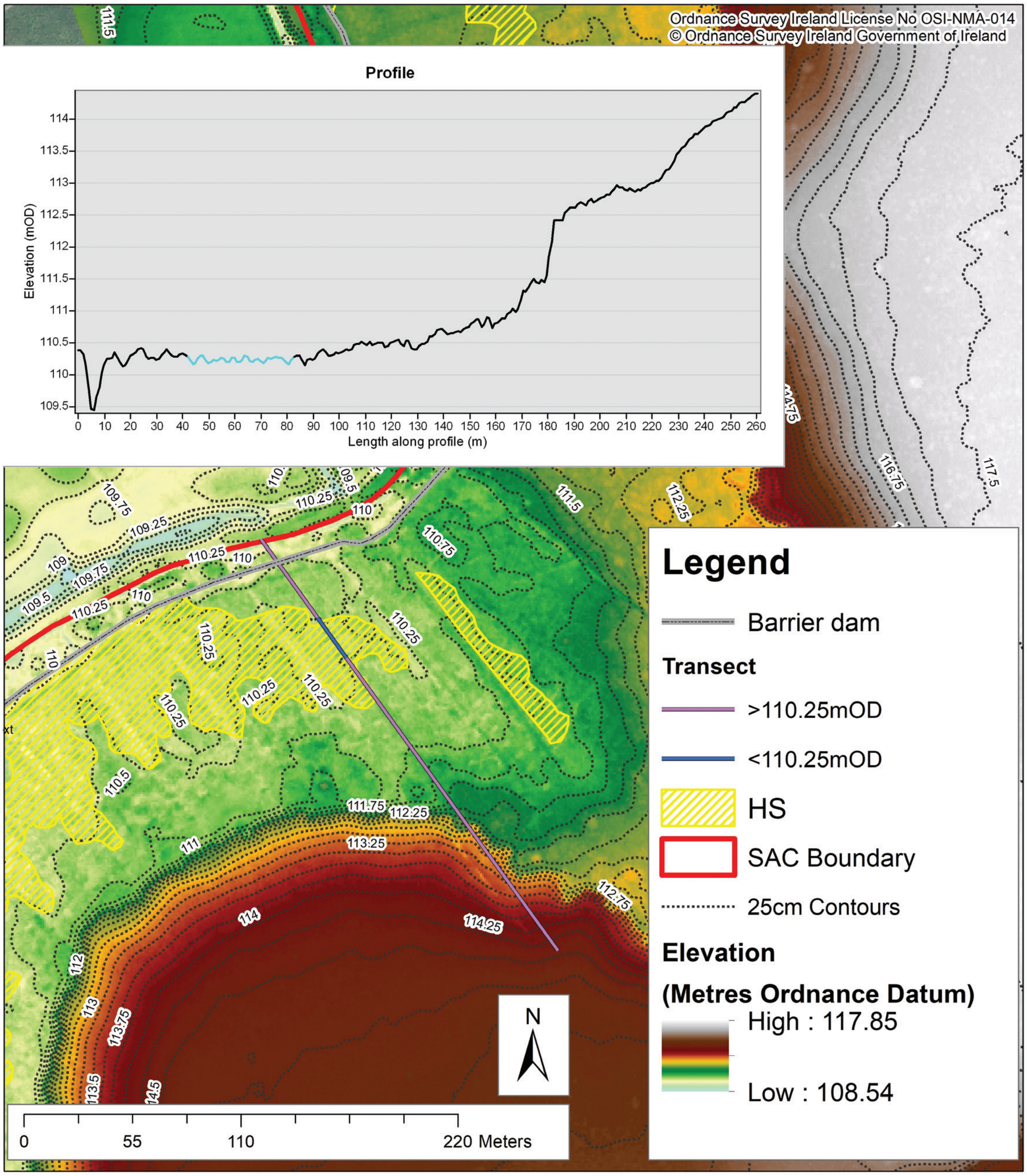

Fig. 7—Topographic profile (corresponding to the transect described in Section 2.3) showing the close correspondence between the boundary of the HS vegetation type and the LS vegetation type at the 110.25 mOD contour interval.

vegetation type LS. The water levels recorded also illustrate the impact of the barrier dam in supporting a water level above ground level in relatively flat locations of the cutover, outside of any depressions, which would not have occurred through drain blocking alone.

While data on the water table pre-construction of the berm is not available, the site had deep open drains (*c.* 1.5m depth) every *c.* 40–50m to delineate turf plots, running from the high bog to an even deeper (*c.* 2m wide and 2m deep) marginal drain, which ran alongside the track (Kelly *et al.* 1995). Thus, the ground surface of the cutover was generally dry to facilitate turf cutting and spreading/drying and the water table was below ground surface across most of the cutover throughout the year (M. Eakin pers. obs.). Comparing those conditions to that represented in Figure 8, the success of the

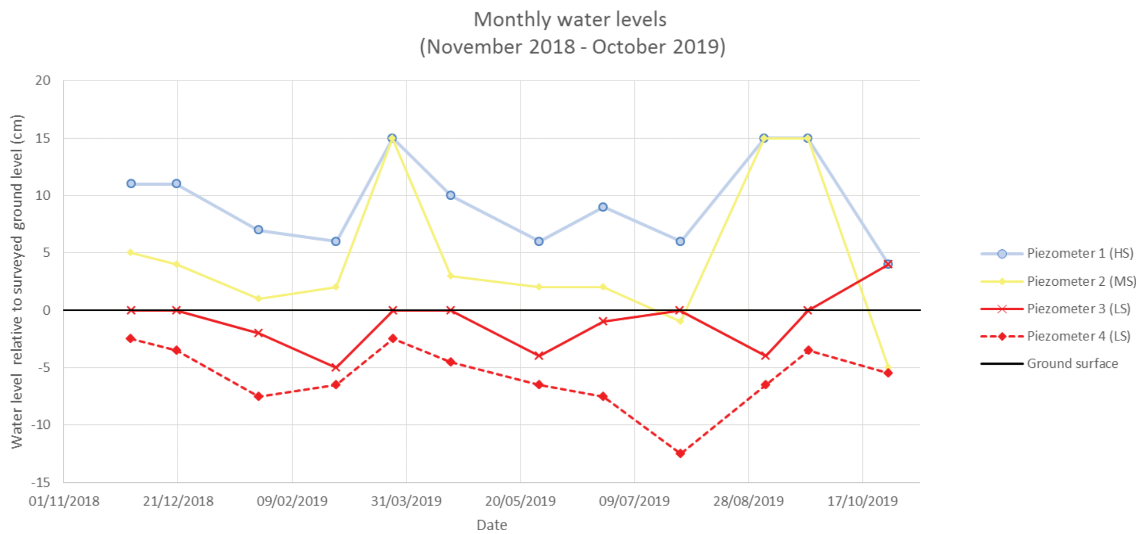

Fig. 8—Hydrograph showing monthly manual measurements recorded from November 2018 to October 2019 in four piezometers located in three different habitat types on the western cutover at Killyconny. Piezometers locations are shown in Figure 2.

berm and drain blocking in raising the water table on the cutover is evident.

DISCUSSION

Any comparison of restoration results between different cutover peatlands needs to take account of both the original peatland and the type and extent of disturbance which impacted on the site. Differences in the succession of the plant species composition post-restoration may partially reflect the different mechanisms of disturbance. The cutover on this study site was hand-cut in a traditional manner up until *c.* 1970. Thereafter, mechanised cutting continued until 2000 using the hopper technique (Fernandez *et al.* 2006) where chunks of peat are cut directly from the high bog margin. Using this technique, drains are inserted in the cutover to delineate turbary right boundaries, to help drain the facebank area where peat is being excavated and to keep the cutover drained so that the harvested peat can dry as rapidly as possible. Machinery is constantly driven over the cutover resulting in peat compaction and giving vegetation little opportunity to recolonise while cutting and harvesting continues. There are, however, localised topographical differences left behind. None of the international studies referred to below were on sites where this form of peat extraction had been in use. For example, those studied by Gonzalez *et al.* (2014) in Canada had been block cut in a traditional manner and the study areas were the trenches created by this cutting method while those studied by Pouliot *et al.* (2012) had either been vacuum milled mechanically at a commercial scale (Canada) and restored by a *Sphagnum* moss transfer method (Rochefort *et al.* 2003) or block cut (Estonia) and abandoned with no restoration.

VEGETATION CHANGES

This study has demonstrated significant vegetation changes over a relatively short period of time (thirteen years) on cutover raised bog following restoration. In the absence of a suitable control, it is not possible to quantify precisely to what extent the observed changes are due to restoration as opposed to natural succession over time. Nevertheless, the success of the berm and drain blocking in raising the water table on the cutover is evident, and the increase in *Sphagnum* cover over time could be used as a proxy indicator of restoration success. Furthermore, restoring 19% of the Killyconny cutover to wet *Sphagnum* rich areas can be adjudged to be a relative success when evidence from elsewhere is taken into consideration, especially in comparison to other similar Irish sites. Tuittila *et al.* (2000) speculated that pre-restoration their study site in Finland showed evidence of succession to dry heath type vegetation. Gonzalez *et al.* (2014) found that abandoned cutovers were dominated by ericaceous shrubs that hampered the spontaneous recovery of a *Sphagnum* dominated system typical of bogs. O'Connell and Geraghty (2017) recorded heather heathland as the most common habitat on the cutover of Girley bog with only 5% of the site mapped as 'actively forming peat'. Smith and Crowley (2020) surveyed 414.6ha of cutover bog across twelve raised bogs in Ireland

and mapped only 6.1% (4.9% when restored areas are excluded) as having a high *Sphagnum* cover and recorded the most common cutover bog habitat (covering 32.3% of the cutovers) as *Calluna vulgaris* dominated cutover with a low (<10% cover) *Sphagnum* cover.

Aside from the relative proportions of different species of *Sphagnum*, the greatest differences between undisturbed natural bogs and restored or abandoned cutover bogs is often in terms of ericaceous species and the typical Cyperaceae (Pouliot *et al.* 2012; Gonzalez *et al.* 2014). A decline of ericaceous shrubs following rewetting was reported by Gonzalez *et al.* (2014), while Pouliot *et al.* (2012) calculated that ericaceous shrubs were two- to three-fold less abundant in re-vegetated peatlands than natural sites. Tuittila *et al.* (2000) highlighted the difficulty in the removal and control of the spread of shrubs in conditions where the water table is below the surface. They found that shrub removal hastened the disappearance of the shrub layer in the wetter sections of rewetted sites where shrubs were already dying, while in the drier sections, removal promoted sprouting and increased shrub layer cover. In our study site ericaceous shrubs are less abundant in vegetation type HS than in typical ARB. However, elsewhere on the cutover, *Calluna vulgaris* is relatively abundant (see Table 1 and 2), occurring at higher cover values than in typical ARB. Furthermore, its cover has doubled in thirteen years from pre-restoration levels along the transect and dominates 44% of the cutover habitat indicating that much of the study site is drier than is necessary for ARB to develop, and that *Calluna vulgaris* may still be spreading from post-abandonment levels.

The typical suite of Cyperaceae have also been reported as dissimilar between re-vegetated and natural bogs with *Rhynchospora alba,* the most abundant vascular species in the hollows of natural bogs, being mostly absent from revegetated sites, where it was replaced by *Eriophorum vaginatum* and *E. angustifolium* (Pouliot *et al.* 2012). Gonzalez *et al.* (2014) note the positive response of *Eriophorum* spp. to rewetting as supporting the effectiveness of re-wetting as a restoration strategy, while Tuittila *et al.* (2000) noted that although wet conditions promoted an increase in the cover of existing *Eriophorum vaginatum* tussocks, new seedlings could only develop in surfaces that were above the water level. At Killyconny, though present, there is as yet no increase in the cover of *Rhynchospora alba* while the cover of *Eriophorum angustifolium* along the cutover plots of the transect has reduced by 75% in the thirteen years since restoration. Similar to the findings of Pouliot *et al.* (2012), for restored peatlands in Canada, the dominant Cyperaceae in HS at the study site is *E. vaginatum* occurring at higher cover values than natural sites.

Graf *et al.* (2015 cited in Andersen *et al.* 2017) noted how in a study of over 71 German peatlands where restoration had been undertaken, typical peatland plants returned to over half of the sites, but some vascular plants such as *Andromeda polifolia* and various *Vaccinium* species did not spontaneously recolonise. *Andromeda polifolia* and *Vaccinium oxycoccos* were recorded very rarely on the cutover at Killyconny; of the 44 quadrats in total (14 in cutover along transect and 30 in the different vegetation types) these species were recorded in only two. Other vascular plants that are characteristic of ARB and absent on the cutover of the study site are *Drosera anglica* and *Menyanthes trifoliata* while *Narthecium ossifragum* and *Rhynchsopora alba* are notably rare. Some of these species were also noted as being rare on the cutover of 11 other raised bogs surveyed by Smith and Crowley (2020) with *Drosera anglica* recorded in only two of 207 open (non-woodland) habitat relevés (1.0%), *Andromeda polifolia* in 5.3%, *Menyanthes trifoliata* in 6.3% and *Vaccinium oxycoccos* in 8.2%. *Rhynchsopora alba* recorded in 13.0% and *Narthecium ossifragum* in 29.0% were also less common than they are in ARB on intact high bog (see Table 2).

SPHAGNUM RECOVERY

The increase in *Sphagnum* cover from 2005 to 2018 on the cutover should be assessed in the context of the *Sphagnum* cover on an intact raised bog. A feature of ARB in Ireland is a *Sphagnum* cover of greater than 40% (Fernandez *et al.* 2014), and only four of the quadrats (Q5–Q8) in the transect and 19% of the cutover area reach these levels. Another consideration is that the species of *Sphagnum* present is critical for certain ecosystem processes, such as peat formation (Renou-Wilson *et al.* 2019). Laine *et al.* (2009) indicate that species such as *S. austinii* and *S. beothuk/S. fuscum*[1] have a high peat-forming capacity; *S. capillifolium*, *S. medium*, *S. papillosum* and *S. subnitens* have a moderate peat-forming capacity; and *S. cuspidatum*, *S. denticulatum*, *S. fallax*, *S. palustre* and *S. tenellum* have a low peat-forming capacity. Of these, only the last three are not listed by the NPWS (2019) as being characteristic of ARB in Ireland. Neither *S. austinii* nor *S. beothuk* were recorded within the quadrats or on the cutover in general, although both these species are present but uncommon on the high bog at Killyconny. Of the moderate peat-forming *Sphagna*, *S. papillosum* and/or *S. subnitens* were present in 29% of the transect quadrats (Q4-Q17) on the cutover surveyed in 2005, but never at a cover of >1% (Table 1). In contrast, all four of the moderate peat-forming species were recorded in the transect quadrats on the restored cutover in 2018, and all these quadrats supported at least one of these species. Therefore, it appears that while the process of peat-formation is not yet as extensive as

[1] *Sphagnum fuscum*, as previously understood, has recently been split into *S. fuscum sensu stricto* and *S. beothuk* (Kyrkjeeide *et al.* 2015); *S. beothuk* is the typical species of lowland raised bogs in Ireland.

on ARB, it has been initiated on the cutover with some diversity of *Sphagna* spp. also establishing.

The relative proportions of *Sphagnum* have been found to differ between restored and natural bogs, with a prevalence of *Sphagnum* species from Section Cuspidata, including *S. cuspidatum*, in the former (Gonzalez *et al.* 2014; Graf *et al.* 2015 cited in Andersen *et al.* 2017), as these species are colonisers with rapid growth rates, particularly when the water table is high. The restored sites studied by Pouliot *et al.* (2012) were an exception where due to the processes involved in restoration by *Sphagnum* moss transfer following vacuum milled cutting, species from Section Acutifolia such as *S. rubellum* and *S. fuscum* gained a short-term advantage in colonisation. In contrast, Gonzalez *et al.* (2014) found that S. *magellanicum* agg.[2] and *S. rubellum* did not show strong signs of recovery on restored sites within a ten-year timeframe. The high frequency of hummock and lawn *Sphagna* (*S. capillifolium*, *S. subnitens*, *S. papillosum* and *S. medium*) as well as *S. cuspidatum* in the study area of Killyconny is in contrast with these findings. This is possibly an artefact of the different mechanisms of disturbance on the cutovers and the proximity of diaspore sources on the high bog, which implies that there is no need for large scale *Sphagnum* inoculation in domestic cutover bog sites with a nearby source of colonising *Sphagna*.

DEVELOPMENT OF ARB

Overall, there is a diverse assemblage of *Sphagna* recolonising the cutover in a relatively short period reflecting the short-term success of the restoration. However, the vegetation still differs from that of typical ARB. *S. austinii* and *S. beothuk*, which are characteristic of good quality ARB in Ireland (Kelly and Schouten 2002; NPWS 2019), are still absent on the cutover. These two species were also very rarely found (1.0% of relevés and never together) in a survey of twelve abandoned (for varying time periods) cutovers by Smith and Crowley (2020). Pouliot *et al.* (2012) identify the following three reasons for the difference in plant species composition between re-vegetated peatlands and natural bogs: 1) an initial high water table of restored sites, 2) stronger competition by hollow species, and 3) growth characteristics of vascular plants. They also found that active restoration reduces the time required for the occurrence of plant species in restored peatlands to resemble the composition of natural peatlands, but that the process is influenced by both the choice of re-introduced species and their specific success in establishing moss carpets. Thus, it may be worth trialling, for example, the active introduction onto cutover of *S. austinii* and *S. beothuk* propagated *ex situ* from local diaspore sources in future restoration projects in Ireland. This would be particularly pertinent in Killyconny where *S. austinii* and *S. beothuk* are very rare on the high bog and thus there may be limited opportunity for colonisation of the cutover via natural dispersal.

The regenerating cutover at Killyconny does not yet qualify as ARB in Ireland as it lacks the presence and/or an abundance of some key indicator species (NPWS 2019). Smith and Crowley (2020) define ARB on cutover according to several criteria, including positive indicator species. Of the eight constant species required, all are present on the cutover at Killyconny, but *Narthecium ossifragum* occurs only rarely. Smith and Crowley (2020) also require four additional positive indicator species for cutover to qualify as ARB. Some, such as *Cladonia portentosa* and *Aulacomnium palustre* are at least occasional on the cutover at Killyconny, whereas others such as *Vaccinium oxycoccos* and *Andromeda polifolia* are rare, and others remain absent, such as *Sphagnum austinii*, *S. beothuk*, *Drosera anglica* and *Menyanthes trifoliata*. NPWS (2019) also highlight the absence of the characteristic hummock-hollow-pool microtopography of ARB in most wet, *Sphagnum*-rich cutover bog. At Killyconny, microtopography is in an early state of development with only localised development of low *Sphagnum capillifolium* ssp. *rubellum* hummocks. Pouliot *et al.* (2011) indicate that microstructures comparable to those in natural bogs can develop on restored boreal peatlands within 10–30 years where *Sphagnum* diaspores have been introduced but may take more than 100 years in cutovers left to revegetate spontaneously. Furthermore, although a trajectory towards the desired *Sphagnum*-dominated communities typical of bogs has been observed on restored sites (Gonzalez *et al.* 2014; Pouliot *et al.* 2012), the plant species composition within the hummock-hollow system has been shown to differ when compared to natural bogs (Pouliot *et al.* 2012). The greatest differences highlighted by Pouliot *et al.* (2012) are in terms of the ericaceous species, the typical Cyperaceae and the relative proportions of different *Sphagnum* species. On Killyconny there are positive signs of natural recolonisation with a diverse assemblage of *Sphagna* already established on the site, but there are some key species still lacking. Furthermore, in addition to those *Sphagn*a typical of ARB, a moderate cover of *S. palustre* has developed in places, particularly in the PF vegetation type though also in small areas of the HS, WM and J vegetation types. Some of these areas also support regenerating young *Betula pubescens* and this may indicate that these areas are in fact developing towards *Sphagnum*-rich bog woodland, which corresponds with the Priority Annex I habitat 91D0.

The conservation target is to create 4.5ha of ARB on the cutover at Killyconny (NPWS 2018) and while this had not yet been achieved, the results above in terms of the numbers of positive indicator

[2] *Sphagnum magellanicum* agg. as formerly known was split into three species, two of which occur in Ireland: *S. medium* and *S. divinum* (Hassel *et al.* 2018).

species colonising the cutover as well the increases in *Sphagnum* cover and *Sphagnum*-rich vegetation (5.0ha of HS) indicate that the site is on the correct trajectory to achieve this target.

RESTORATION POTENTIAL AND TOPOGRAPHY

It is evident through comparison of the DTM and the vegetation mapping that topography has played a significant role in influencing the areas of the cutover that have successfully regenerated. During the development of the National Raised Bog SAC Management Plan (NPWS 2018) a preliminary metric based on the model used to define areas of DRB was developed (Appendix 2, NPWS 2018). This involves identifying areas of suitable topographic gradient (≤0.3%) and areas of enclosed depressions that have a minimum catchment area of 5,000m^2. As the metric only considers surface topography and does not consider factors such as peat depth or hydraulic conductivity of the peat, it is used as an indicator of areas most likely to rewet following implementation of restoration measures such as drain blocking. The metric outputs for the cutover at Killyconny shows reasonable correspondence between areas predicted to become peat-forming and those mapped as vegetation type HS; with 41% of areas predicted to become peat-forming being mapped as vegetation type HS (Figure 9). If all habitats reported as flooded, wet or very wet are included (i.e. EW, WM and PF) along with HS then the correspondence increases to 60%. PF and WM are indeed likely to be peat-forming habitats while the water levels in EW are possibly too high for *Sphagnum* colonisation and thus peat formation. However, the metric appears to have under-predicted the potential for establishment of peat-forming conditions at Killyconny, with the extent of vegetation type HS expanding beyond the areas identified by the metric. This is due to the establishment of vegetation type HS on slopes in excess of 0.3% (outside of topographic depressions), which would not have been considered suitable by the metric. While there remains some uncertainty regarding the exact reasons for the difference in some areas, it is clear that the presence of the berm has resulted in the development of additional areas of *Sphagnum*-rich vegetation beyond what would be expected through drain blocking alone. This is particularly evident along the edge of the berm where slopes in excess of 1% have been identified, yet these areas are mapped as vegetation type HS as a result of permanent shallow inundation caused by the marginal berm.

Overall, while further research is required from a wider range of sites to determine the conditions required to establish peat-forming habitats on cutover bog, it is clear from the study of Killyconny Bog that topography and hydrology are of key importance in determining restoration potential. The results demonstrate that the preliminary hydrological metric for predicting peat-forming habitats on cutover areas (NPWS 2018) is of merit. However, further work is required to refine the criteria used. For example, the metric should account for areas of steeper slope (>0.3%) where measures to sustain a high water table (such as bunding) can be employed. Furthermore, the metric fails to account for meteorological conditions which are likely to have a significant influence on slope and contributing catchment area thresholds. At Killyconny drain blocking alone is likely to have resulted in development of small pockets of vegetation type HS across the cutover. However, it is clear that the marginal berm enhanced the success substantially, enabling vegetation type HS to develop across a larger area and on steeper slopes than would otherwise have been possible. The marginal berm at Killyconny was constructed along parts of the cutover where the baseline topographic conditions were not suitable for the development of peat-forming habitat. There is close correspondence between the areas mapped as drier habitats (non-peat-forming) and metric outputs for the cutover at Killyconny. Thus, using modelling techniques will allow conservation practitioners to design restoration works that have a better chance of success with the obvious concomitant cost-benefits. Consideration (using modelling techniques) of implementing 'enhanced' restoration measures such as berms within cutover bog is now standard practice within the current raised bog restoration programmes being implemented by the NPWS and a berm somewhat similar to that on Killyconny was designed for Ardagullion Bog SAC and constructed in January 2019.

The limited hydrological monitoring data provides a clear indication of the importance of hydrology in influencing restoration outcomes, with close correspondence between hydrological conditions and the vegetation types that have developed. The monthly measurements, while useful are at risk of missing extremes in water levels, particularly times during times summer months when evapotranspiration rates are greatest and water levels may drop, limiting the potential for *Sphagnum* to develop. The results highlight the benefits of cross-disciplinary studies that link ecological and hydrological variables that will help in optimising future restoration measures.

MANAGEMENT ISSUES

Further restoration measures at Killyconny involving the blocking of 11.8km of drains across the high bog and additional cutover areas are scheduled for 2021 as part of *The Living Bog* project. These are necessary to help restore the hydrological integrity of the bog and to help the site to reach its ARB

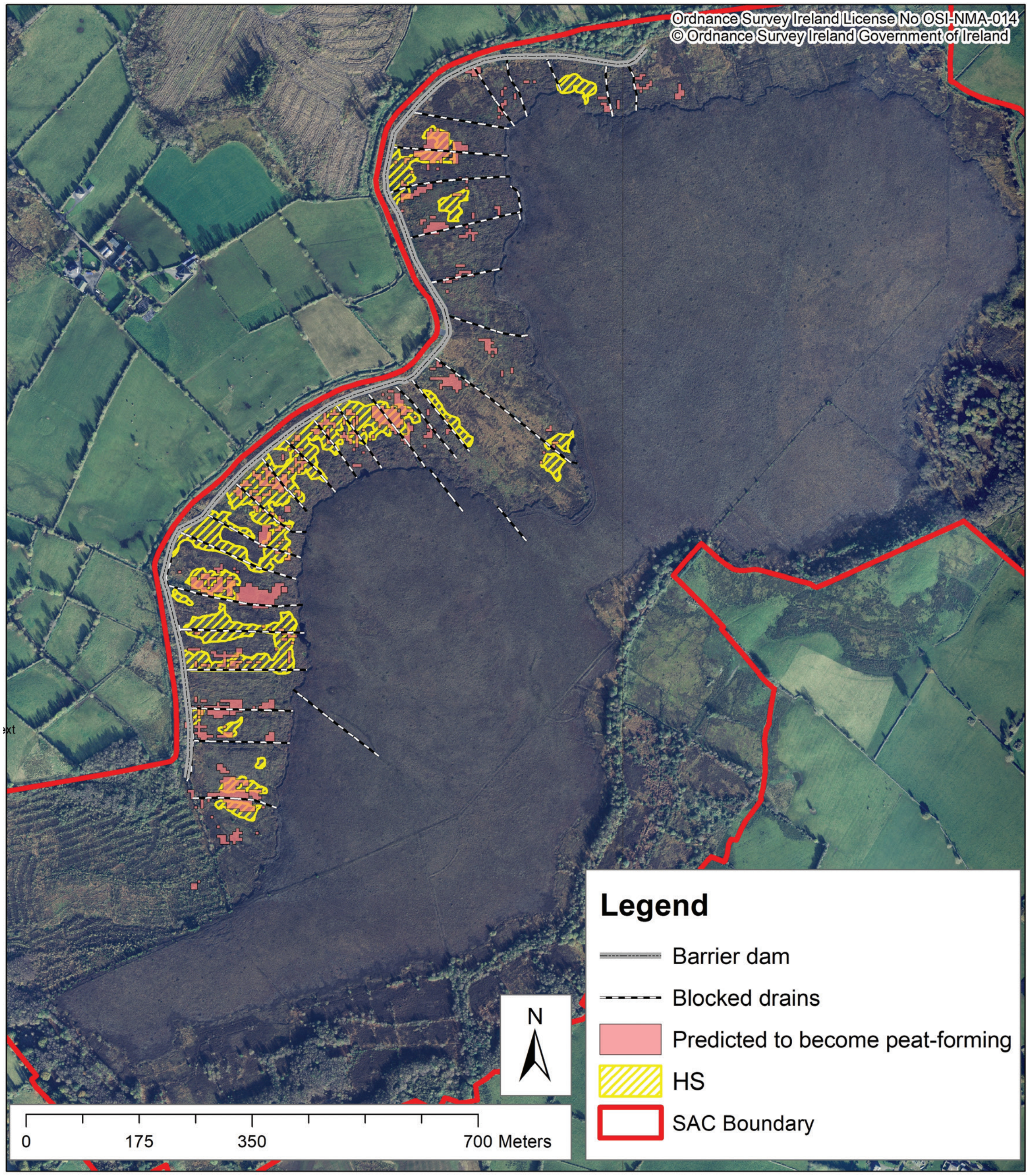

Fig. 9—Correspondence between areas predicted to become peat-forming and those mapped as vegetation type HS.

target of 8.7ha on the high bog. With respect to greenhouse gas emissions and climate change mitigation, the restoration of the cutover in this study is likely to have reduced emissions in line with the findings of numerous studies such as Renou-Wilson *et al*. (2019) and Regan *et al*. (2020). However, more site-specific studies or at least research specific to the vegetation types recorded in this study are necessary. In any case, the dominance of low *Sphagnum* habitat categories, which have been found to be a net carbon source (Swenson *et al*. 2019) is likely to mean that the cutover as a whole remains a carbon source. Future management of the site faces a number of restoration choices to improve the extent and quality of *Sphagnum*-rich cutover areas, such as whether additional berms should be built, scrub and trees removed and whether the active introduction of *Sphagnum* diaspores is necessary. The importance of restoring the lagg zone, if possible, around the bog is also recognised (Schouten *et al*. 2002) and Howie and van Meerveld (2011) outline the importance of lagg zones in terms of the hydrological restoration of a raised bog. A potential constraint on rewetting cutover bog and laggs is the possibility of raising the water table in adjacent agricultural land. At Killyconny an efficient marginal drainage network along the western perimeter of the site prevents this. Where this is not the case, restoration plans may need to be curtailed, or agreements may be required with neighbouring landowners to permit rewetting and, potentially, the restoration of wetlands (including peat-forming systems) on adjacent farmland. Such agreements could be facilitated through novel results-based agricultural schemes aimed at meeting targets under the Irish government's *Climate Action Plan 2019*.

Another potentially impacting or limiting factor relates to ammonia deposition with over 90% of Ireland's raised bogs (including Killyconny) modelled by Kelleghan *et al*. (2019) as being above the critical annual mean NH_3 thresholds derived by Bobbink and Hettelingh (2011). Recent monitoring has recorded levels even higher than that modelled for Killyconny (Kelleghan *et al*. 2020). This problem of atmospheric nitrogen pollution in ombrotrophic bogs in mainland Europe has been well documented where it has been implicated in the invasion of bogs by *Molinia* and *Betula* (Tomassen *et al*. 2004). While Ireland has, until recently, had low levels of atmospheric nitrogen pollution, it has experienced continuously increasing emissions of ammonia since 2011 (Kelleghan *et al*. 2019), exceeding the limits set by the National Emissions Ceilings Directive (NECD) (2016/2284) (European Union 2016) for the first time in 2016 (Environmental Protection Agency 2018). The extent to which the vegetation on Killyconny is currently impacted on by these elevated levels is unclear. However, casual observations on the high bog have noted the presence of *Xanthoria* spp. on some of the *Pinus* spp., as well as the growth of algae on *Calluna vulgaris* stems and bleached/decaying *Sphagnum* hummocks.

CONCLUSION

It is estimated that 19% of the cutover bog habitat at Killyconny is on a trajectory towards typical ARB species composition. However, across much of the study site, the cover of species such as *Eriophorum vaginatum* and *Molinia caerulea* remains high and may indicate that there are processes slowing down or preventing the re-establishment of ARB. For example, the relatively frequent occurrence of *Sphagnum palustre* as well as the occurrence of *Juncus effusus* indicates that all the vegetation is not wholly ombrotrophic, which may reflect some groundwater interactions. Although not yet considered ARB, the 19% of the Killyconny cutover that is classed as regenerating is clearly of conservation significance as a peat-forming habitat that supports assemblages of several specialist species. The restoration works at Killyconny demonstrate how water levels can be raised and peat-forming vegetation can become established in a relatively short period of time. However, 56% of the site is still dominated by dry vegetation with a low *Sphagnum* cover; 44% by *Calluna vulgaris* dominated vegetation and 12% by *Molinia caerulea* dominated vegetation. Thus, further enhanced restoration work such as cell bunding and additional marginal berms may need to be considered to rewet these areas. The modelling techniques outlined above will be integral to the design of such future works and will ensure the best chance of success. Furthermore, while large scale *Sphagnum* inoculation is not recommended, small scale experimental transfer of the less common *Sphagna* such as *S. beothuk* may be worth trialling on Killyconny.

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