PLANT COMMUNITIES IN THE GRADIENT FROM RAISED BOG TO FEN IN A NEAR-INTACT LAGG ZONE IN CARROWNAGAPPUL BOG, IRELAND

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ABSTRACT

Despite the importance of lagg zones in the function and restoration of raised bog systems, there have been limited studies on their vegetation communities and environmental characteristics. Given their importance and lack of study, the vegetation in the near-intact lagg zone in the south-south-west of Carrownagappul Bog in Co. Galway was sampled along four transects in July 2020. Cluster analysis separated the vegetation, encompassing 97 species, into 5 vegetation types. There were affinities between these vegetation types and a range of Irish Vegetation Classification (IVC) bog, heath, grassland and fen communities, as well as two Habitats Directive Annex I habitat types, transition mires and alkaline fen. In addition, a population of the Annex II listed Marsh Fritillary (*Euphydryas aurinia* (Rottemburg, 1775)) was recorded from the area. In general, the vegetation communities reflected a gradient of increasing alkalinity, moisture and nutrient status from ombrotrophic raised bog to minerotrophic fen. The diversity of the vegetation over a small area and its near-natural conditions underscore the conservation significance of the lagg zone, and these findings accentuate the hydrological perspective that restoration of the lagg should, where possible, be a key element in raised bog restoration. The current lack of a characterisation of the lagg types found in Ireland is a barrier to developing a sound restoration and conservation management strategy.

INTRODUCTION

The lagg of a raised bog is a transition zone where hydrology and ecology are influenced by run-off from the ombrotrophic (rain-fed) bog and surface or groundwater flow from adjoining mineral-rich environments. These areas possess a number of distinct hydrological and hydrochemical gradients resulting in the occurrence of specific plant communities (Howie and van Meerveld 2011). The variable water chemistry can lead to the development of a diverse range of vegetation types, including wet woodland, swamp and rich and poor fen, which contrast markedly with the vegetation on the high bog (Mackin *et al*. 2017). In Ireland there are no raised bogs that are completely intact, and most laggs were lost long ago through drainage and land reclamation (Fossitt 2000). Osvald (1949), commenting on study visits to Ireland undertaken in 1935 and 1937, noted that 'The margins of these bogs are generally spoiled through peat cutting… In some places, however, the margin and the lagg of proximal parts is still to be seen…'. Thus, the few remaining relatively intact lagg zones are of high conservation importance and can harbour populations of rare species, such as *Eriophorum gracile*, which has been recorded in lagg areas around Sharavogue Bog in Co. Offaly (Conaghan 2014) and Sheheree Bog in Co. Kerry (Conaghan and Sheehy Skeffington 2009).

Despite their value to nature conservation, no comprehensive survey of Irish laggs has been undertaken and there are a limited number of studies of their vegetation communities and environmental characteristics. The lagg at Sheheree has been described as the most intact lagg zone known in Ireland (Cross 1990), while the lagg at Sharavogue is considered to possess one of the best examples of wet lagg vegetation in the country (Conaghan 2014). A large proportion of the Sheheree lagg is colonised by carr woodland in which *Alnus glutinosa*, *Betula pubescens* and *Salix* spp. are dominant, with low-growing marsh vegetation dominated by *Carex rostrata*, *Juncus articulatus* and *Calliergonella cuspidata* growing along the woodland edges (Conaghan and Sheehy Skeffington 2009). The lagg at Sharavogue has developed along the base of an adjoining hill on shallow cutover that has been undisturbed for several decades (Mackin *et al*. 2017). It is described in detail by Conaghan (2014) and summarised as containing areas of wet *Alnus glutinosa*–*Phragmites* *australis* woodland, dry *Betula pubescens*-*Molinia caerulea* woodland, *Schoenus nigricans*-*Carex* fen and a range of ombrotrophic cutover vegetation types.

Additional lagg studies have been carried out on Raheenmore and Clara by Kelly and Schouten (2002), who noted some small areas around these bogs that were under the influence of groundwater. A number of vegetation communities were described in this study, along with an assessment of the hydrology and hydrochemistry. However, it was noted that the water-table levels were relatively low, which would not reflect the hydrological conditions in a typical lagg zone. Furthermore, there was no distinction made between communities that formed part of the original lagg and those that originated through the removal of peat down to the level of groundwater influence. Abbeyleix Bog is an example of a secondary lagg, i.e. formed by peat extraction to a depth where recolonising vegetation is influenced by groundwater) of high conservation interest that has developed on cutover bog but has then been left undisturbed for decades or centuries. Here, a high water table is maintained due to run-off from the bog on one side and from the mineral soils and esker streams on the other side, plus groundwater discharges from beneath the bog and the adjacent eskers (Ryan*,* Fernandez and Cross 2019). This lagg contains a high diversity of wet woodland, fen and petrifying spring habitat types (McCorry *et al.* 2015; Ryan *et al.* 2019; Smith and Crowley 2019, 2020a), including the EU Habitats Directive (92/43/EEC) Annex I habitats petrifying springs (7220), transition mire (7140) and bog woodland (91D0), as well as the nationally rare greater tussock-sedge dominated alder swamp woodland (Cross *et al.* 2010). Additionally, a number of rare or uncommon species, including the liverwort *Cephalozia pleniceps*, which is listed as vulnerable in the bryophyte *Red List* (Lockhart *et al.* 2012) and *Pyrola minor*, have been recorded from the lagg at Abbeyleix Bog.

The rand of a raised bog occurs towards the edge of the main bog expanse where the gradient increases markedly to form a rand slope, which typically supports a somewhat drier vegetation (Thom *et al.* 2019). More simply, the rand can be defined as the outward-sloping margin of a raised bog situated between the bog and the lagg (Wheeler and Shaw 1995). On a fully intact raised bog, flow is generally from the centre to the edge of the bog exiting into a surrounding lagg stream or fen (Thom *et al.* 2019). However, as no completely intact raised bogs remain in Ireland, the flow patterns are usually highly altered and drainage impacts have resulted in long-term subsidence across the entire raised bog dome. Examples of these drainage impacts have been studied at Clara, where historical subsidence has resulted in the apparent lowering of the bog surface by an estimated 10m (van der Schaff 2002), while over a 28-year period Regan *et al.* (2019) recorded subsidence impacts 900m from the bog edge with subsidence increasing towards the bog edge and levels in excess of 1m recorded up to 170m from the bog margin.

Howie and van Meerveld (2011) argue that restoration of the lagg should be a key element in raised bog restoration, since maintaining a high water level in the lagg helps to sustain the dome of water in the raised bog peat body. The presence of the lagg also helps to regulate excess water leaving the bog during times of high rainfall and run-off. However, successful lagg restoration is dependent on the hydro-geological setting of the bog system, on the changes that have occurred in the regional ground-water system, and on the extent to which they can be reversed (Schouten *et al.* 2002). For example, the restoration of a functioning lagg along the north of Clara West might not be possible due to the lowered water levels in the River Brosna (van der Schaff and Streefkerk 2002) brought about by the arterial drainage scheme of the river by the Office of Public Works in the 1950s. Since the hydrological conditions of a lagg zone are unique to each bog, site-specific research is needed to identify the potential for lagg zone restoration and to identify any remnant lagg communities present so that they are not adversely affected by the restoration works. Restoration projects must also take into account any possible consequences of raised water levels for adjacent landowners and effects on local geohydrological conditions due to reduced groundwater discharge or increased aquifer recharge.

Given the importance of the lagg in raised-bog ecology and hydrology, we have sampled and described the vegetation of a near-intact lagg at Carrownagappul Bog in Co. Galway to address gaps in our understanding of lagg vegetation and ecology. The objectives of this study are to describe the plant communities of the lagg zone of Carrownagappul Bog, to identify the main environmental factors that influence plant species composition, and to assess the conservation value of the lagg as a part of the raised bog ecosystem.

MATERIALS AND METHODS

SITE DESCRIPTION

Carrownagappul Bog is located 2km north of Mountbellew in the east of Co. Galway and is designated under the EU Habitats Directive (92/43/EEC) as a Special Area of Conservation (SAC 001242) for the priority Annex I habitat Active Raised Bog (Natura 2000 code 7110), as well as the Annex I habitats Degraded Raised Bog (7120) and Rhynchosporion Vegetation (7150) (Fig. 1). The SAC is 485.7ha in extent and contains 326.9ha of high bog (of which 45.3ha were classed as Active

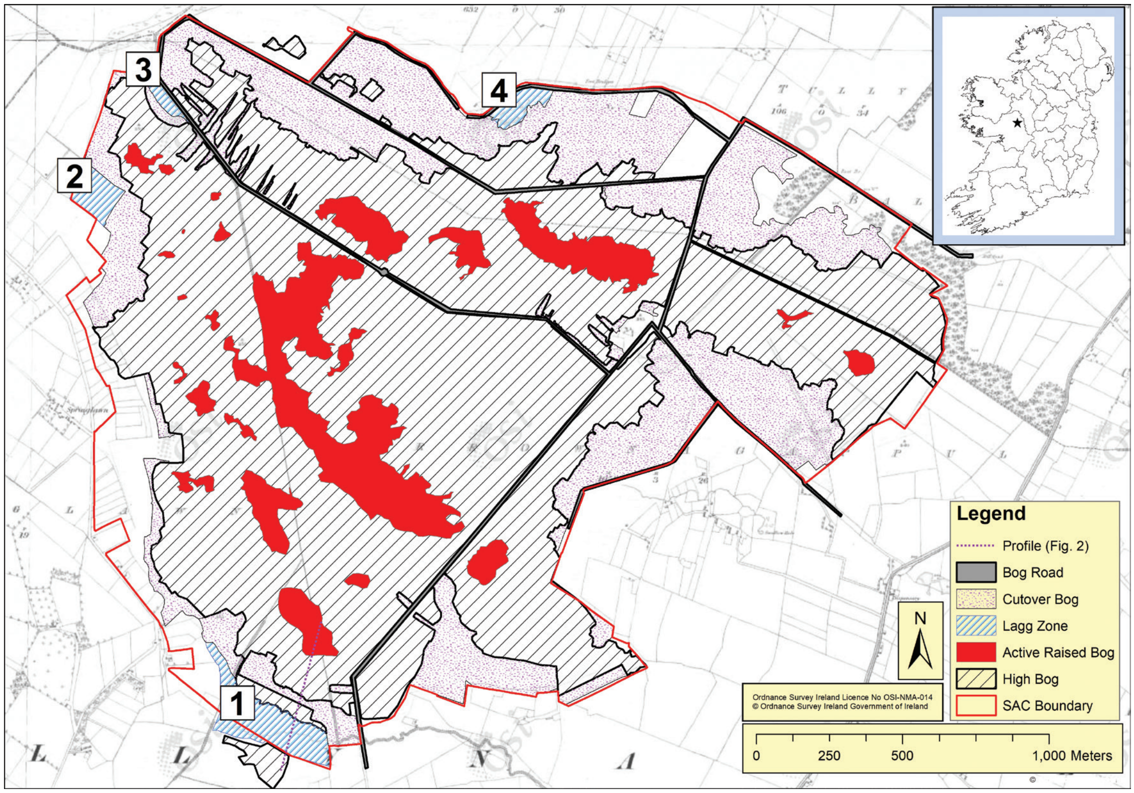

Fig. 1—The location of Carrownagappul Bog in Ireland and the locations of the four lagg zones recorded on the site. The background map is the Ordnance Survey Ireland Historic 6 inch map dated 1829–41. Note the presence of a stream in the most southerly lagg zone.

Raised Bog (ARB) by The Living Bog survey of 2021 using the methods of Fernandez *et al.* 2014), with the remaining 158.8ha comprising mainly cutover bog (108.9ha) at different stages of revegetation. Kelly *et al.* (1995) estimated the extent of the bog from the 1840s Ordnance Survey maps at 636ha. A number of bog roads thought to have been constructed in the 1950s also cross through the bog. These roads were constructed using round stone laid upon a base of furze cuttings and were intended only for light traffic such as donkey and carts. The heavy machinery associated with mechanised domestic peat harvesting from the 1970s onwards led to damage and so parts of these roads were then upgraded. Turf cutting occurred around almost the entire margin, but largely ceased in 2012 as part of a government policy to halt cutting within designated sites (Fernandez *et al.* 2014), though one plot continued to be cut until 2018. The site was also managed for Red Grouse by the Mountbellew-Moylough Game Preservation Association from the late 1990s until the mid-2010s and was considered to be the most productive raised bog for Red Grouse in Ireland (Scallan 2015). The underlying bedrock of the area is mapped by the Geological Survey of Ireland (GSI) as pale grey clean skeletal limestone and Visean Limestones (undifferentiated). The presence of a swallow hole 400m to the east of the bog indicates that the limestones in the area are pure and susceptible to karstification (Kelly *et al.* 1995).

Restoration works began in 2003 with the damming of 4.5km of high bog drains and were continued as part of The Living Bog project in 2018–21 with the damming of 19.5km of drains on the high bog, 21.5km of drains on the cutover, and 5.5km of drains associated with tracks. Additionally, a barrier dam (see Mackin *et al.* 2017 for a description of the methods) was built in the north-east of the site in 2021 and a conifer plantation was removed by stump flipping, with the associated bog levelled and smoothed as a trial of the methods, as described by Campbell and Robson (2019). In total, the project has so far installed 2,952 peat dams and 575m of linear peat-barrier dam, as well as two heavy-gauge reinforced plastic dams. As part of the project, the entire area of cutover within the SAC was surveyed and four distinct areas of lagg vegetation noted (Fig. 1). Little if any cutting appears to have taken place in one of these areas (Area 1), thus making it a near-intact lagg zone. The other lagg zones are described briefly as follows:

Area 2: a semi-intact lagg zone affected by historical peat cutting. It may have been part of the original lagg area, as it occurs in the outer extent of the area mapped as bog in the historic 1840s Ordnance Survey Map (Fig. 1). This area is a mosaic of rich fen, poor fen and transition mire. Distinguishing species present include *Dactylorhiza traunsteinerioides*, *Carex diandra*, *Carex nigra*, *Pinguicula vulgaris*, *Philonotis calcarea*, *Sphagnum contortum*, *Sphagnum subnitens*, *Campylium stellatum*, *Scorpidium cossonii* and *Chara virgata*.

Area 3: a secondarily developed lagg in an area where peat has been removed through turf cutting. This area is a mosaic of poor fen and transition mire.

Area 4: a semi-intact lagg zone that may have been part of the original lagg area. This area is a mosaic of poor fen/flush and transition mire. Distinguishing species present include *Silene flos-cuculi*, *Carex nigra*, *Carex echinata*, *Sphagnum palustre*, *Sphagnum squarrosum*, *Sphagnum fallax* and *Hylocomium splendens*.

A large fire damaged the site in 2011, burning 185ha of high bog as well as much of Area 1, the lagg zone studied in this report, which lies in the south-south-west of the site. In the 1840s Ordnance Survey maps, this lagg zone is mapped as an area where two bogs converge, separated by a stream. While no peat cutting appears to have occurred within Area 1, some historical hand cutting occurred to the north (coming in from the track in the east), which is likely to have led to a reduction in the contribution of ombrotrophic water into the lagg from the high bog further north. The topography of the area grades from relatively gently sloping high bog (corresponding to active raised bog) to an increase in the slope towards the margin, where some peat cutting occurred; and a remnant of high bog remains. The slope increases more rapidly along the rand before breaking into a relatively flat area corresponding to the lagg, and the topography rises again towards degraded areas of raised bog further south (Fig. 2).

VEGETATION SAMPLING

To sample the vegetation in the near-intact lagg area, four transects of six relevés were taken across two days in July 2020 (Fig. 3). Relevé 1 in each transect was placed on the edge of the high bog and comprised typical degraded raised bog vegetation. Relevés 2–5 continued downslope through mostly *Molinia caerulea*-dominated vegetation. Relevé 6 was located at the bottom of the slope in wet fen or transition mire vegetation. Each transect was located approximately 40m apart and varied in length from 76m to 124m, while the elevation ranged from 68.3m to 71.3m. The distance in metres of each relevé centre from the high bog/rand boundary was measured using ArcMap 10.6; relevé 1 in each transect was on the high bog and thus was assigned a negative distance value. An additional relevé was also recorded at the bottom of the slope in transition-mire vegetation. The nomenclature follows Stace (2019) for vascular plants, Blockeel *et al.* (2021) for bryophytes and Dobson (2018) for lichens. The relevé size was 2m x 2m and the abundances of all vascular plant, bryophyte and lichen species were recorded using the Domin scale (Kent and Coker 1992).

VEGETATION DATA ANALYSIS

Prior to analysis, Domin values were transformed to the mid-point values of percentage cover ranges,

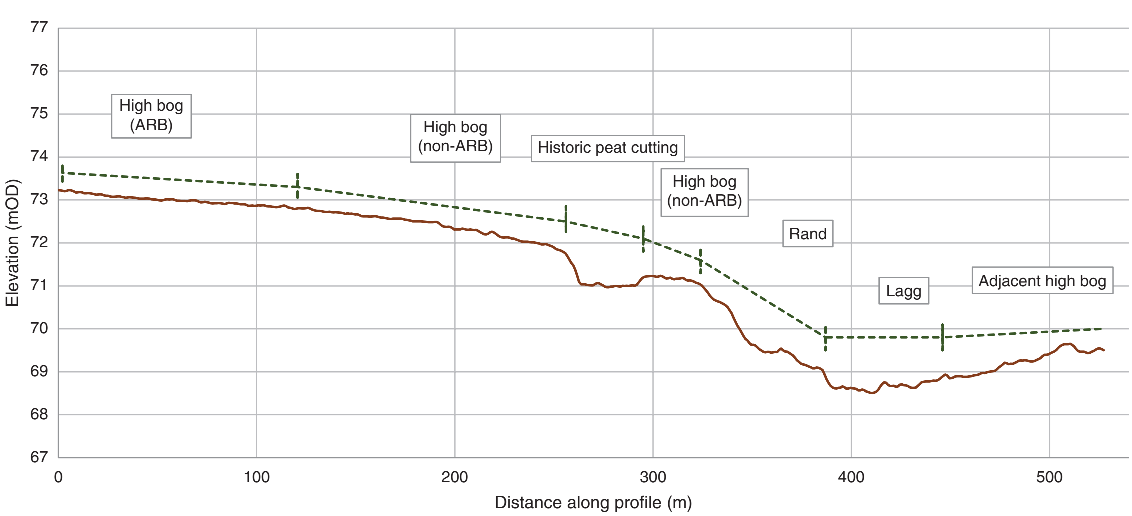

Fig. 2—Elevation profile showing zones and the terminology used. Note that zero is an arbitrary point taken within Active Raised Bog to illustrate the wider context of where the lagg is situated relative to the main body of the high bog.

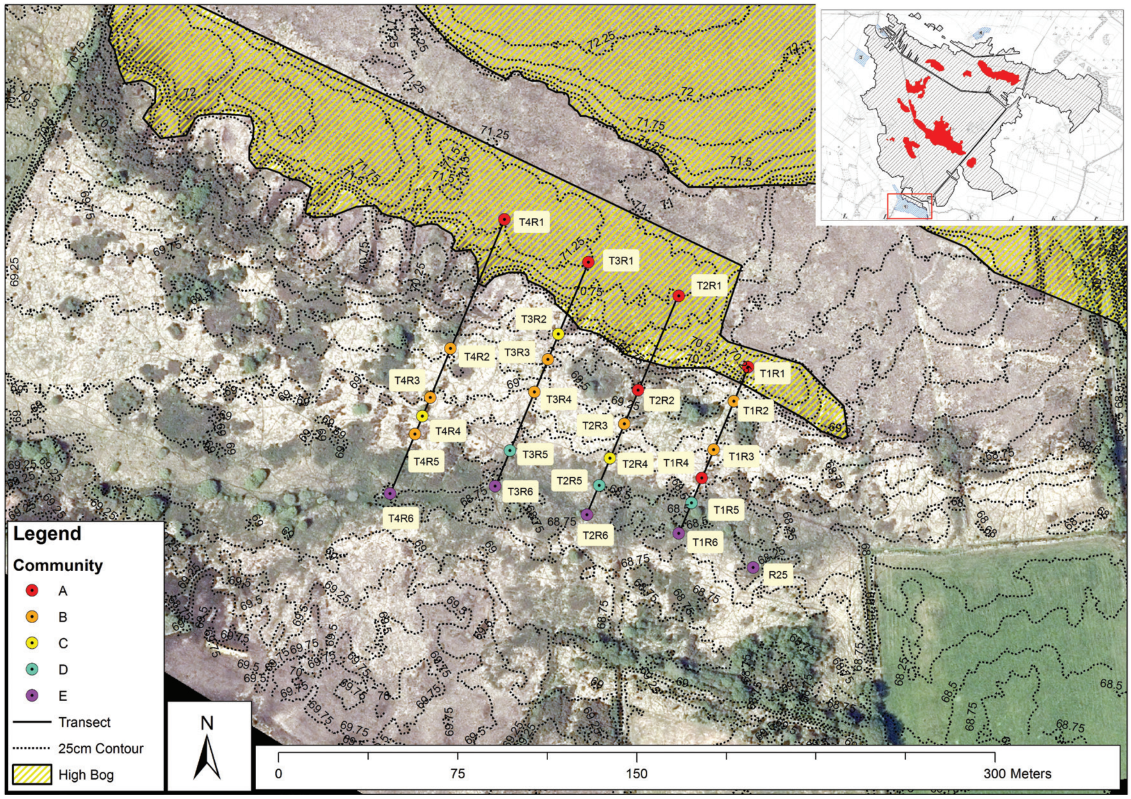

Fig. 3—The location of transects, relevés and contours in the lagg of Carrownagappul Bog (Area 1 of Fig. 1). Community A comprises of degraded raised bog vegetation, B is heathy grassland dominated by *Molinia caerulea*, C is a transitional community, D is alkaline fen and E is transition mire. Background Aerial photograph taken by Bluesky in May 2020.

following Perrin (2019). K-means cluster analysis using a matrix of Bray-Curtis distances (Legendre and Legendre 1998) among the 25 relevés was used to describe lagg zone vegetation communities. Solutions ranging from three to seven clusters were produced and assessed. Silhouette analysis, which numerically evaluates the dissimilarity within clusters compared with the dissimilarity among clusters, was used to assist in determining the best solution. Characteristic species for each cluster were identified using Indicator Species Analysis (Dufrêne and Legendre 1997). Relevés and clusters were plotted (Fig. 4) in a reduced (two-dimensional) species space using non-metric multidimensional (NMS) ordination of Bray-Curtis distances among relevés (Legendre and Legendre 1998). The best solution from twenty runs with random starting configurations was used as the starting configuration for the final ordination. All statistical analyses were performed in the R statistical environment. Package 'vegclust' was used to perform K-means clustering, package 'labdsv' was used for Indicator Species Analysis, and NMS ordination was implemented using the function metaMDS in package 'vegan'.

The data from the 25 relevés were entered into the ERICA tool (Perrin 2020), through which the affinities of each relevé with the communities defined by the IVC (National Parks and Wildlife Service, BEC Consultants and National Biodiversity Data Centre 2019) were analysed. This analysis procedure uses a version of fuzzy clustering called noise clustering, in which each relevé is assigned a degree of membership to each of the communities defined by the IVC (De Cáceres *et al.* 2010; Perrin 2015, 2018). ERICA was also used to obtain the mean values for Ellenberg's indicator values for each relevé, the reference values coming from Hill, Preston and Roy (2004) and Hill *et al.* (2007). These are environmental proxy scores for moisture, light, reaction/acidity and nitrogen/fertility. The Ellenberg value for a relevé is the mean value of each species weighted by its abundance in the plot. Ellenberg values range from 1–9: high scores for moisture indicate wetter conditions; high scores for light indicate brighter more open conditions; high scores for reaction indicate more basic conditions; and high scores for nitrogen indicate more fertile conditions. To contextualise, O'Neill *et al.* (in press) adapting from Wheeler *et al.* (2009) proposed

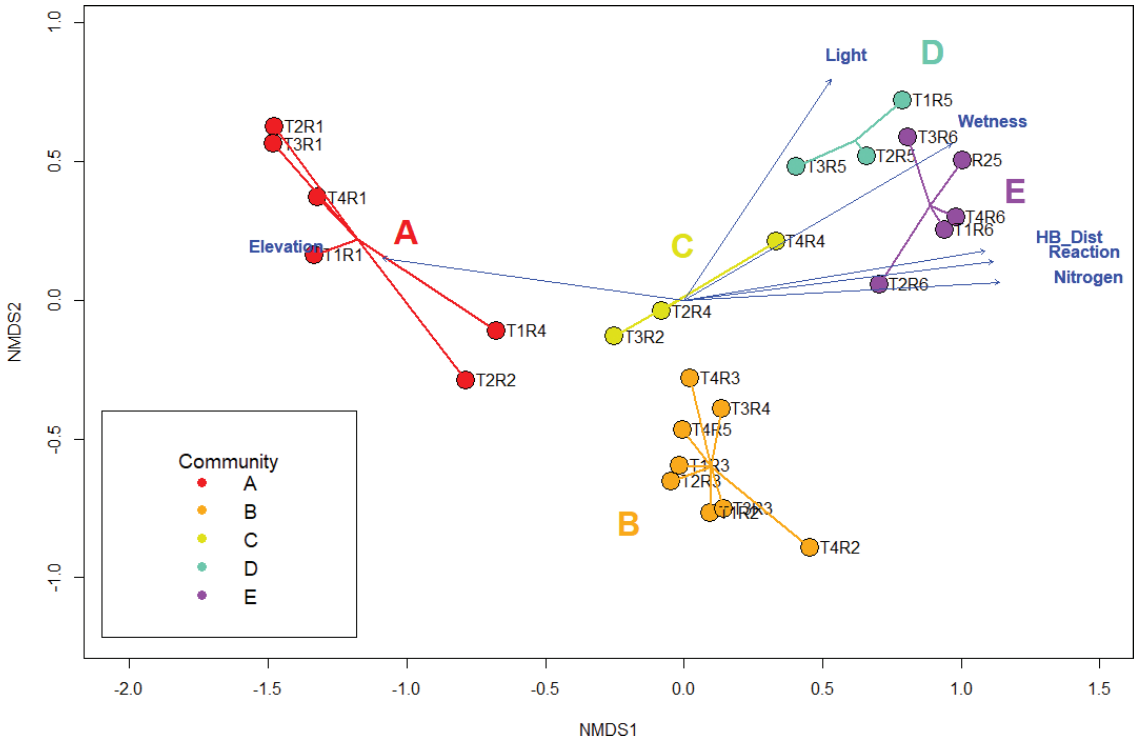

Fig. 4—NMS ordination of the transect plots with cluster memberships shown. Also shown are correlations of environmental variables (Elevation = elevation above sea level in metres, HB_Dist = distance from the high bog/rand boundary) and proxies (Ellenberg values for Reaction, Nitrogen and Light) with NMS dimensions.

the following categories. For reaction: 1–3.5 = acidic, 3.6–4.5 = base-poor, 4.6–5.5 = sub-neutral and 5.6–9 = base-rich. For fertility 1–2.5 = oligotrophic, 2.5–5.5 = mesotrophic, 5.6–7.5 = eutrophic and 7.6–9 = hypertrophic. Ellenberg values, elevation and distance from the high bog/rand boundary were fit to the NMS ordination using function envfit in package 'vegan'.

HYDROLOGICAL ANALYSIS

In addition to the vegetation sampling, the flow paths and catchment of the area were modelled using the Hydrology Toolbox within ArcGIS® based on LiDAR data collected for the area in 2012 (Fig. 5). A topographic survey of the area was carried out in May 2021 using a Leica Geosystems GS14 (Hexagon, Stockholm, Sweden) to reaffirm that the topography of the area was unchanged since the 2012 LiDAR survey. The topographic cross-sections of transects are presented in Fig. 6a-d. Field measurements of specific electrical conductance (SEC) and temperature of water were also measured in May 2021 using an YSI Pro30 Meter (Xylem Inc, New York, USA) in locations where it was possible to fully submerge the SEC probe.

RESULTS

VEGETATION

A total of 97 species were recorded in the 25 relevés with 64 vascular plants, 31 bryophytes and 2 lichens.

A five-cluster solution was chosen as the best representation of the lagg zone vegetation. This solution had a mean silhouette width of 0.36. A 3-cluster solution had a marginally better silhouette width (0.38), but the five-cluster solution provided a better characterisation of lagg zone communities. The five vegetation communities are described in Table 1 and range from ombrotrophic bog (community A) at the high bog margin through heathy *Molinia* grassland (communities B and C) to wet fen in the lagg proper (communities D and E). This gradient is reflected from left to right in the NMS ordination (Fig. 4). NMS Axis 1 was significantly ($p < 0.001$) correlated with lower elevation ($r = 0.990$) and increasing distance ($r = 0.987$) from the high bog margin.

The environmental proxy scores (Ellenberg values) for moisture, reaction (acidity) and nitrogen (fertility) show the same pattern as the vegetation data. The means of these combined Ellenberg values

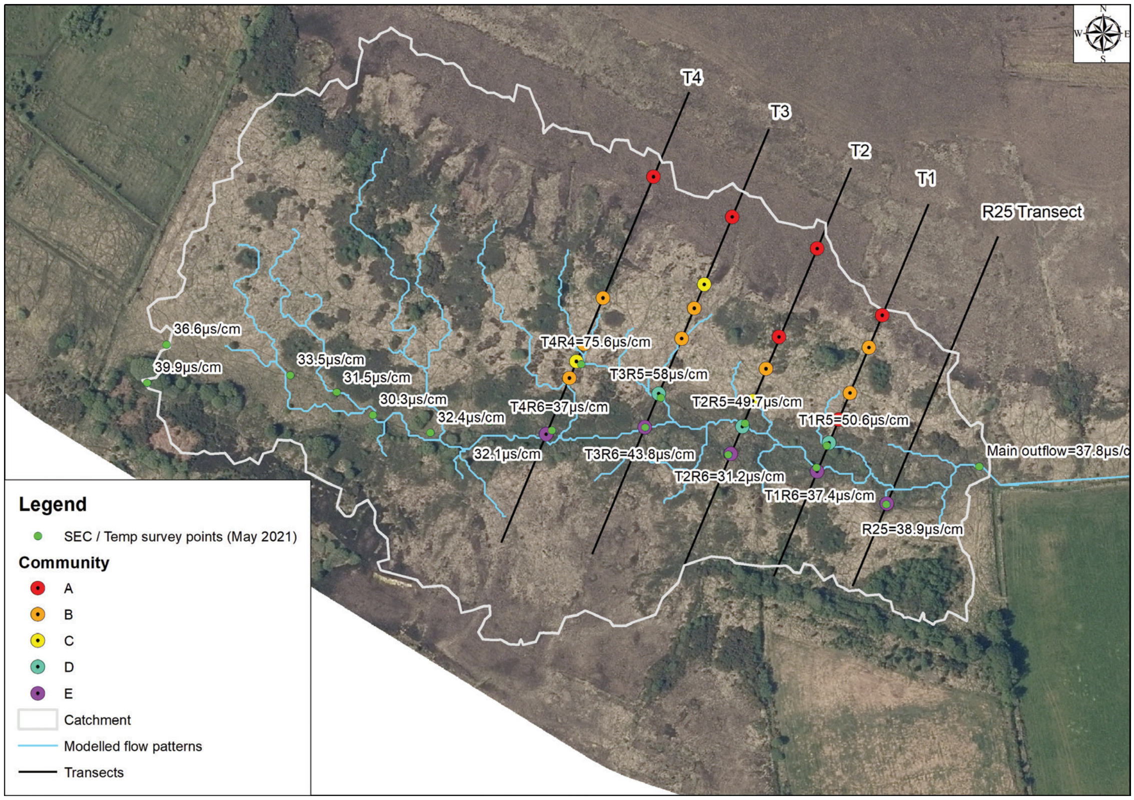

Fig. 5.—The location of the topographic cross-sections, catchment boundary, modelled flow patterns and conductivity measurement sites (SEC taken on 12 May 2021) through the study area. Background Aerial photograph taken by Bluesky in May 2020.

(Hill, Preston and Roy 2004; Hill *et al.* 2007) for the relevés in communities D and E were higher than the other communities, and Community A had the lowest score (Table 3). There was little difference among communities in the combined Ellenberg value for light. The fit of all environmental variables to the NMS ordination was significant (all $p < 0.001$), indicating strong environmental control of the vegetation. NMS Axis 1 was correlated with higher Ellenberg values for nitrogen ($r=0.998$), reaction ($r=0.992$), wetness ($r=0.863$) and light ($r=0.553$), whereas Axis 2 was correlated with higher wetness ($r=0.505$) and light ($r=0.833$) values (Fig. 4).

Community A: this was the least species-rich of the five communities with 15.2 (± 1.1) species/ 4m^2. Four of the relevés were located on the high bog and two (T1R4 and T2R2) were on the rand, i.e. the slope down to the lagg proper. The topography in both of these instances is locally elevated and therefore these plots are likely to be less influenced by surface water flow and further from the water table than other plots along the slope. The NMS ordination (Fig. 4) shows that these two plots were somewhat separated from the four high bog plots, particularly along the first axis, which appears to follow a gradient of wetness (dry to wet) and reaction (acid to less acid). This vegetation has closest affinity (39.3%) with the IVC community BG2B *Erica tetralix – Andromeda polifolia* bog. Affinity rises to 58.9% when the two plots that are not on the high bog are excluded. The IVC describes this as a community of raised bog that usually occurs on deep acidic, ombrogeneous and oligotrophic peats. Unsurprisingly, as it is located at the edge of the high bog, it has a low *Sphagnum* cover. While it is not considered Annex I active raised bog (7110), it is nevertheless an important supporting habitat for the active raised bog at Carrownagappul. The high frequency of the alien invasive moss *Campylopus introflexus* in this community is likely to be a result of the fire that affected the area in 2011.

Community B: this is a fairly species-poor (19.0 ± 1.4 species/ 4 m^2) heathy grassland community, all relevés (n = 8) of which occur on the rand. The NMS ordination (Fig. 4) shows that these plots are clearly separated from all other plots along the second axis. *Molinia caerulea* dominated at high cover values with *Potentilla erecta* also being constant. *Succisa pratensis* was found in 62.5% of the plots, and as larval webs of the Habitats Directive Annex II listed Marsh

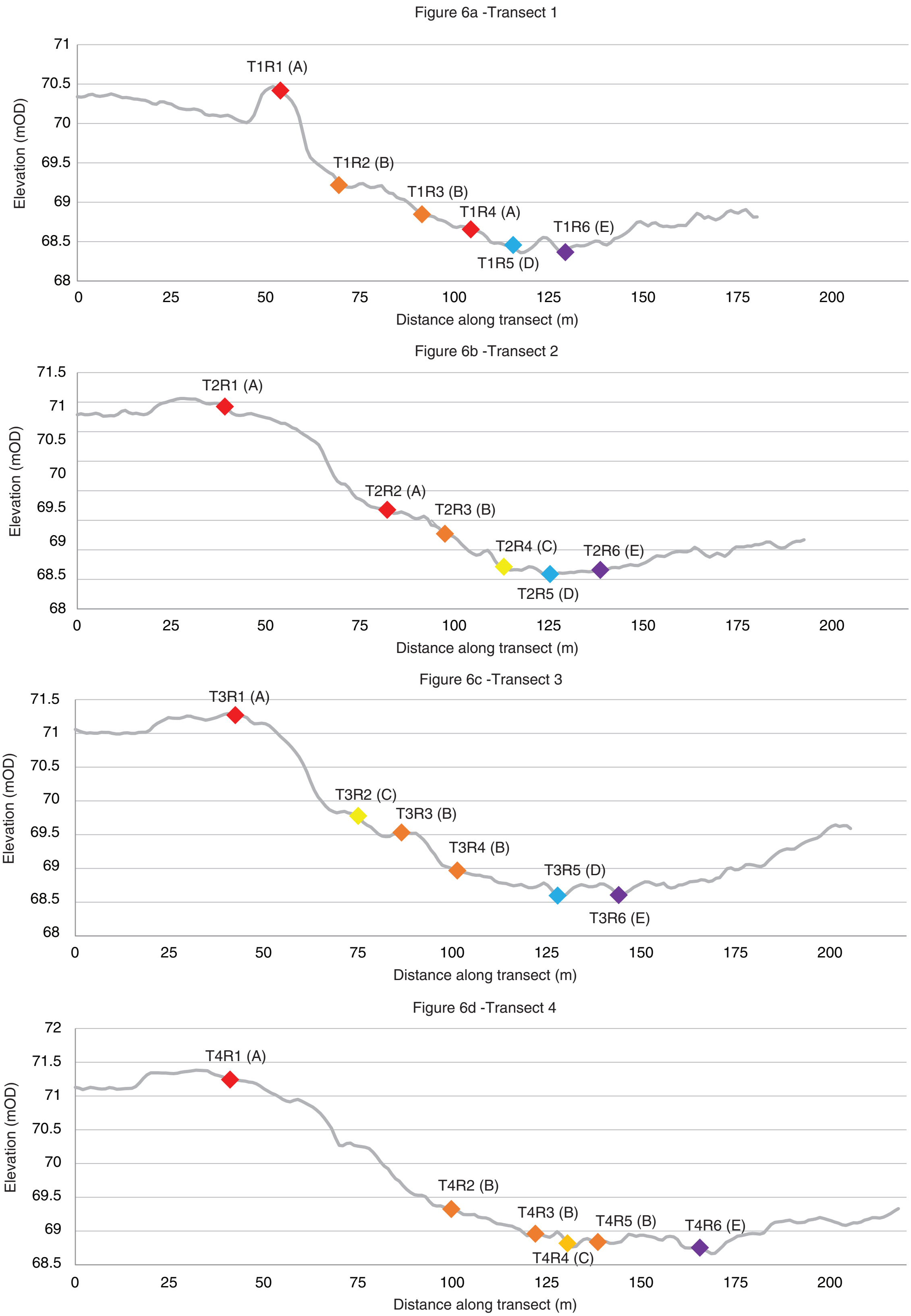

Fig. 6a–d.—The topographic cross-sections to illustrate the position of each plot along the topographical gradient.

Table 1—Synoptic table of species in vegetation communities of the near intact lagg at Carrownagappul Bog. The percentage of relevés in which a species is found in a given vegetation type is summarised using frequency classes delineated by Roman numerals as follows: V (81–100%); IV (61–80%); III (41–60%), II (21–40%) and I (0–20%). The figures in brackets refer to the range of cover values of a species occurring within the group of relevés using the Domin scale. Species that do not have a frequency class of >40% for any vegetation type are not listed in the table. Significant indicator species, as determined using Indicator Species Analysis (Dufrêne and Legendre 1997), are grouped together for each habitat type and marked with an outline.

n	*A*	*B*	*C*	*D*	*E*
	6	*8*	*3*	*3*	*5*
Species/4m² (*± SE*)	15.2 ± 1.1	19.0 ± 1.4	31.3 ± 2.7	31.0 ± 3.6	22.8 ± 1.6
Calluna vulgaris	V (7–9)	III (1–4)	V (1–5)	II (1)	
Sphagnum rubellum	V (1–4)		IV (2)		
Erica tetralix	V (3–5)	III (1–2)	IV (3–4)	II (3)	
Hypnum jutlandicum	V (2–7)	II (1)	IV (1–2)		
Eriophorum vaginatum	IV (2–5)				
Cladonia portentosa	IV (1–2)				
Eriophorum angustifolium	IV (2–4)	I (1)		IV (1–2)	
Calypogeia fissa	IV (1–2)	I (1)	II (1)		
Sphagnum tenellum	III (1–4)				
Molinia caerulea	IV (2–7)	V (7–9)	V (5–6)	IV (3)	IV (3–6)
Pseudoscleropodium purum	I (1)	V (1–6)	IV (2–4)		
Potentilla erecta	III (2–3)	V (2–4)	IV (2–3)	II (2)	
Carex pulicaris		III (1–2)	V (2–3)	II (2)	
Trifolium pratense			IV (2–3)		
Succisa pratensis	I (2)	IV (1–4)	V (3–4)	IV (1)	III (1–3)
Briza media			IV (3)	II (1)	
Sphagnum subnitens	II (1)	I (1)	IV (3)		
Carex hostiana		III (1–2)	V (3–4)	II (4)	II (1–4)
Dactylorhiza maculata		II (1–2)	IV (1–2)		
Equisetum palustre	II (1–3)	V (2–4)	V (4–5)	IV (3–5)	V (2–4)
Luzula multiflora	I (+)	V(1–2)	V (1–2)	II (1)	I (2)
Carex lepidocarpa				V (1–5)	I (1–3)
Hydrocotyle vulgaris				V (2–3)	II (2)
Carex rostrata				V (3–6)	III (3–4)
Carex nigra		I (2)	II (3)	V (5–6)	IV (3–5)
Filipendula ulmaria				IV (1)	
Salix cinerea		I (3)		V (1–3)	II (2–3)
Mentha aquatica		I (1)	II (3)	V (2–4)	V (1–3)
Comarum palustre		I (3)		V (4)	V (2–4)
Equisetum fluviatile			II (2)	V (3–4)	V (1–4)
Menyanthes trifoliata			II (+)		V (7–9)
Juncus articulatus			II	IV (2–3)	V (4–5)
Carex panicea	IV (1–4)	IV (1–2)	V	V (2–5)	III (1–3)

Table 1 (Continued)—Synoptic table of species in vegetation communities of the near intact lagg at Carrownagappul Bog. The percentage of relevés in which a species is found in a given vegetation type is summarised using frequency classes delineated by Roman numerals as follows: V (81–100%); IV (61–80%); III (41–60%), II (21–40%) and I (0–20%). The figures in brackets refer to the range of cover values of a species occurring within the group of relevés using the Domin scale. Species that do not have a frequency class of >40% for any vegetation type are not listed in the table. Significant indicator species, as determined using Indicator Species Analysis (Dufrêne and Legendre 1997), are grouped together for each habitat type and marked with an outline.

n	*A*	*B*	*C*	*D*	*E*
	6	*8*	*3*	*3*	*5*
Campylopus introflexus	IV (1–3)				
Odontoschisma sphagni	III (1–2)		II (1)		
Cephalozia connivens	III (1)				
Trichophorum germanicum	III (2–3)				
Juncus conglomeratus	II (2)	V (1–3)	IV (2)	IV (2–3)	
Myrica gale	I (6)	I (5)		V (1–5)	IV (3–7)
Carex echinata	I (4)	II (1–3)	IV (1)	II (2)	III (1–2)
Holcus lanatus	I (2)	IV (2–4)	V (2–3)	IV (2–3)	IV (4–5)
Agrostis canina	I (1)	IV (1–4)	V (+–4)	V (2–3)	V (3–4)
Anthoxanthum odoratum		V (3–5)	V (3–5)	IV (1–4)	III (1–3)
Hypericum pulchrum		IV (1–3)	IV (2)	II (+)	
Juncus effusus		III (1–4)	II (2)		
Cirsium dissectum		II (4)	IV (1–6)	IV (1–4)	
Calliergonella cuspidata		II (3–4)	IV (1–4)	IV (5)	IV (1–5)
Polygala serpyllifolia		II (1–2)	IV (1)		
Campylium stellatum		II (1)	V (1–3)	V (1–3)	II (2)
Ranunculus flammula			IV (1–3)	V (3–5)	V (3–5)
Cardamine pratensis			IV (1–2)	IV (+–1)	III (1–2)
Calliergon giganteum			II (3)	IV (2–5)	
Bryum pseudotriquetrum			II (3)	IV (1)	II (1)
Epilobium palustre				IV (3–5)	III (2–4)
Calliergon cordifolium				IV (1–3)	II (2–7)
Galium palustre				IV (1–2)	III (2–3)
Pedicularis palustris				IV (1–2)	III (+–2)

Other species present that do not occur in >40% of the relevés of any vegetation type: Community A only: *Drosera rotundifolia* (I), *Juncus squarrosus* (I), *Kurzia pauciflora* (I), *Leucobryum glaucum* (I), *Narthecium ossifragum* (II), *Peltigera membranacea* (I) and *Sphagnum papillosum* (I). Community B only: *Carex binervis* (I), *C. flacca* (I), *Cirsium palustre* (II), *Galium saxatile* (II), *Juncus inflexus* (II), *Lophocolea bidentata* (I), *Rhytidiadelphus squarrosus* (I), *Rubus fruticosus* agg. (I), *Salix x multinervis* (I) and *Sphagnum palustre* (I). Community C only: *Anagallis tenella* (II). Community D only: *Brachythecium rivulare* (II) and *B. rutabulum* (II). Community E only: *Angelica sylvestris* (I), *Carex diandra* (I), *Galium uliginosum* (I), *Potamogeton polygonifolius* (I) and *Veronica scutellata* (I). Species in multiple community types: *Aulacomnium palustre* (A, II; B, I; C II), *Hylocomium splendens* (A, I; B, II; C, II; D, II), *Dicranum bonjeanii* (A, I; C, II), *Festuca rubra* (B, II; C, II), *Ctenidium molluscum* (B, I; C, II), *Plagiomnium undulatum* (B, I; C, II), *Agrostis stolonifera* (B, I; C, II; E, I), *Danthonia decumbens* (B, I; D, II), *Kindbergia praelonga* (B, I; E, I), *Fissidens adianthoides* (C, II; D, II), *Caltha palustris* (C, II; D, II; E, I), *Drepanocladus cossonii* (C, II; D, II; E, I), *Juncus bulbosus* (C, II; D, II; E, I) and *J. acutiflorus* (D, II; E, I).

Table 2—Mean percentage affinities of lagg vegetation communities with Irish Vegetation Classification (IVC) communities. An IVC type with an affinity of 1–5% is given as <5, of 0.1–1% as <1 and of <0.1% as –. Where an IVC type has an affinity of <20% for any one lagg vegetation type, it is included as other.

	BG2B	*FE1C*	*FE2B*	*FE2F*	*FE3A*	*GL1C*	*GL1D*	*HE4D*	*Other BG*	*Other FE*	*Other GL*	*Other HE*	*Other*
A	39.3	–	–	–	–	–	–	<1	11.2	–	–	49.3	–
B	–	–	–	–	–	<5	51.0	44.7	–	<1	<1	<5	<1
C	–	12.4	<1	<1	1.6	25.1	18.5	<5	<5	<5	15.0	17.4	<1
D	–	21.1	<5	5.0	57.8	<1	<1	–	–	9.9	<5	<1	<5
E	–	<5	29.3	42.7	<5	<1	<1	<1	–	22.0	<1	–	<1

Table 3—Means and standard errors of the combined Ellenberg values for the relevés in each vegetation community.

	Light	*Wetness*	*Reaction*	*Nitrogen*
A	7.1 ± 0.1	6.7 ± 0.2	2.3 ± 0.1	1.8 ± 0.1
B	7.0 ± 0.0	7.2 ± 0.1	3.8 ± 0.1	2.5 ± 0.1
C	7.2 ± 0.1	7.3 ± 0.4	4.3 ± 0.2	2.4 ± 0.1
D	7.4 ± 0.1	8.4 ± 0.2	4.9 ± 0.1	2.7 ± 0.2
E	7.6 ± 0.1	9.0 ± 0.2	4.5 ± 0.1	3.0 ± 0.1

Fritillary (*Euphydryas aurinia*) have been recorded in the general area, this community may be important in maintaining population of the species. This vegetation type has close affinity with two distinct IVC communities: GL1D *Molinia caerulea* – *Potentilla erecta* – *Agrostis stolonifera* grassland and HE4D *Molinia caerulea* – *Potentilla erecta* – *Erica tetralix* heath (Table 2). Both loosely correspond with the UK's National Vegetation Classification (Rodwell 1991) category M25 *Molinia caerulea* – *Potentilla erecta* mire, which is described as a community of moist, but well aerated, acid to neutral peats and peaty mineral soils in the wet and cool western lowlands of Britain that occurs over gently-sloping ground, marking out seepage zones and flushed margins of sluggish streams, water-tracks and topogenous mires, but also extending onto the fringes of ombrogenous mires.

Community C: this is a species-rich (31.3 ± 2.7 species/ 4 m^2) community, which is poorly defined here, as only three relevés were taken within it. The NMS ordination (Fig. 4) shows that these relevés separated from the others (Community B) taken on the rand along the second axis. Communities B and C were combined into one cluster in the three-cluster solution and split in the four-cluster solution. The main difference between the two communities was the lower abundance of *Molinia caerulea* and greater frequency of other species in Community C. *Molinia caerulea*, though constant, had a lower cover than in Community B. Characteristic species included *Briza media*, *Carex pulicaris, Succisa pratensis, Trifolium pratense* and *Sphagnum subnitens*. This vegetation has no clear affinity with IVC communities, with the highest affinity (25.1%) being for GL1C *Molinia caerulea* – *Succisa pratensis* grassland and the second highest (18.5%) being for GL1D. However, there are also significant affinities for communities within the heaths division (19.4%) as well as the fens and mires division (19.0%), while the affinity for the grassland division is 58.6% overall. The IVC notes that where there is a good population of *Succisa pratensis*, GL1C communities can be important for the Annex II listed Marsh Fritillary (*Euphydryas aurinia*) (National Parks and Wildlife Service *et al*. 2019), and indeed, larval webs were noted within one of the relevés in this community.

Community D: this is a species rich (31.0 ± 3.6 species/ 4 m^2) fen community. All relevés (n = 3) occurred towards the base of the slope, and the Ellenberg values indicate that this is the least acidic (4.9 ± 0.1) of the five communities described here. This is reflected in its 96.0% affinity with IVC communities from the fens and mires division with greatest affinity (57.8%) for FE3A *Carex nigra* – *Ranunculus flammula* fen, followed by FE1C *Carex panicea* – *Carex viridula* fen (21.1% affinity). The IVC indicates that where these communities support brown mosses, the vegetation corresponds to the Annex I habitat alkaline fens (7230). Thus, the presence of species such as *Campylium stellatum*, *Bryum pseudotriquetrum*, *Fissidens adianthoides* and *Scorpidium cossonii* within this community in the lagg of Carrownagappul suggests that the vegetation here corresponds to alkaline fen. *Sphagnum contortum*, described by Rydin *et al*. (1999) and Atherton *et al*. (2010) as being one of the most base-demanding *Sphagna*, was also found in this community outside but close to one of these relevés, as was *Pinguicula vulgaris*. This community was typically found in areas of ponded water, with little evidence of active flow. Therefore, the influence of any groundwater seepage is much stronger than it would be if it were diluted from water inputs from other sources.

Community E: this is a moderately species rich (22.8 ± 1.6 species/ 4m^2) peatland community. All relevés (n = 5) occurred at the base of the slope, and the Ellenberg values indicate that this is the wettest (9.0 ± 0.2) of the five communities described here. *Menyanthes trifoliata* grew vigorously and dominated the vegetation while *Myrica gale* was frequent, indicating some water movement. *Carex diandra* was only recorded in one relevé but occurred at high cover. *Calliergonella cuspidata* dominated the bryophyte layer and *Calliergon cordifolium* and the brown mosses *Campylium stellatum* and *Scorpidium cossoni* were occasional. Affinity with the IVC communities is split between the different communities of the mire (FE2) group, for which there is 91.9% affinity overall. Greatest affinity is with FE2F *Menyanthes trifoliata – Calliergonella cuspidata* mire (42.7%) and FE2B *Carex limosa – Menyanthes trifoliata* mire (29.3%). The vegetation here has similarities with the Habitats Directive Annex 1 habitat transition mires (7140) and is of high conservation value. The groundwater influence appears to be diluted to some extent by the accumulation of acidic surface water running off the bog and flowing along the water track from the north-west. This is illustrated by the modelling of the flow paths (Fig. 5) where, in most instances, Community E occurs along the main modelled flow path.

HYDROLOGY

SEC and temperature measurements revealed all areas to have relatively low SEC values (<80µS/cm) indicating relatively low levels of dissolved ions (Fig. 5). Nevertheless, there were small deviations in SEC and temperature, which may provide an indication of where water movement was more active and therefore where greater dilution of the influence of any groundwater seepage occurred. The mean (±SE) of the SEC values at Community D was 52.8 (±2.6) µS/cm with a temperature of 11.7 (±0.1) °C, while mean values at Community E were lower: 36.1 (±2.0) µS/cm and 10.8 (±0.1) °C. These patterns were evident elsewhere across the study area in general, with lower values recorded within areas where active water movement was observed. However, there is one exception to this on Transect 2, where the flow path (Fig. 5) appears to pass through T2R5 (Community D) rather than T2R6 (Community E). The topographic survey revealed that the elevation was slightly lower at T2R5 (68.196 mOD) than T2R6 (68.234 mOD), indicating that the predicted flow paths were accurate. However, field measurements of SEC indicate higher values in T2R5 (49.7µs/cm) than T2R6 (31.2µs/cm), which suggest that T2R5 may be a local topographic depression, where water is relatively stagnant, and the main flow path is through T2R6. Although measurements from one round of sampling are not conclusive, the consistent observation of lower SEC and temperature measurements within areas classified as Community E when compared to Community D indicate that the flow may be more active through Community E than D. Only one relevé (T4R4, Community C) in communities A, B or C had sufficient water to obtain a SEC and temperature reading, and this relevé (which supported the highest abundances of the brown mosses *Scorpidium cossonii* and *Campylium stellatum* of any relevé) had the highest of all readings recorded, with a SEC of 75.6µS/cm and a temperature of 16.8°C. These readings were recorded in relatively small pools of stagnant water, where there are limited inputs of low SEC rainwater and relatively small upstream catchment areas, which would result in dilution with low SEC rainwater.

DISCUSSION

The lagg zone studied here is characterised by a relatively steep slope from the raised bog edge down through the rand to wetter, more base-rich and nutrient-rich (though still oligo-mesotrophic) fen communities. The location of each community appears closely associated with topographic setting. The raised bog margin (Community A) is dry and *Calluna*-dominated as a result of its position at the top of the slope. Flow of water and nutrients from the bog down the rand facilitates the presence of *Molinia*-dominated vegetation (Communities B and C). It is likely that microtopography and the influence of base-rich, but nutrient-poor groundwater emerging on the slope are responsible for the differences in vegetation in this area. Community C, in particular, appears to be transitional between the bog-surface water-influenced vegetation of the rand (Community B) and the groundwater-influenced lagg (Communities D and E). In the lagg proper, groundwater seepage is the strongest driver of the vegetation (Community D). Finally, at the bottom of the lagg is the wettest vegetation (Community E). Here, the groundwater influence appears to be diluted to some extent by the accumulation of acidic surface water running off the bog and flowing along the water track (i.e. the main flow path through the area where surface water accumulates) from the north-west.

The lagg zone in the study area at Carrownagappul Bog, though only *c*.5ha in extent, has a diverse array of species and habitats and is of high conservation value as one of the few near-intact laggs remaining in Ireland. The bog itself is listed as an SAC for one priority Annex I habitat (active raised bog) and two other Annex I habitats (degraded raised bog and Rhynchosporion depressions), and this study establishes that perhaps two more Annex I habitats (alkaline fen and transition mire) are present in the lagg zone, with the site also supporting a population of the Annex II listed Marsh Fritillary (*Euphydryas aurinia*). From a nature conservation perspective, the findings of this study underscore the conclusions of Howie and van Meerveld (2011) and Schouten *et al*. (2002) that restoration of the lagg based on hydrological analysis should, where possible, be a key element in raised bog restoration, as it helps to maintain a high water table within the peat mass of a bog. The findings also support the principle outlined by Howie and van Meerveld (2016) that greater knowledge of the variability in laggs will improve the decision-making process for conservation authorities when designating conservation sites and designing restoration measures for damaged bogs.

Given the widespread loss of lagg zones across Irish raised bogs, it is imperative that laggs such as the one studied here are provided with adequate protection to ensure the continued supply of ombrotrophic bog water and base-rich groundwater. Historical peat cutting between the lagg and adjacent high bog to the north/north-west is likely to have reduced the supply of ombrotrophic water and therefore impacted species composition. Further drainage in the surrounding area has the potential to result in groundwater upwelling, which may reduce the supply of groundwater to the lagg. Given the karstified nature of the underlying bedrock, even drainage beyond the immediate vicinity of the lagg zone may present a risk. Due to the designated status of the bog as a SAC, activities within and adjacent to the bog that may have an impact on the conservation condition of the site are regulated. However, drainage is an activity that is regularly carried out surrounding designated sites with little consideration of the potential impacts. Ensuring adequate regulation of such activities is key to ensuring that any existing remnant laggs such as this one are conserved. The SAC boundary at Carrownagappul Bog (Fig. 1) should be reviewed, as it omits part of the lagg zone, and the review should be expanded to all raised bog SACs and Natural Heritage Areas (NHAs) to ensure that any lagg zones or other supporting habitats in those sites have also not been omitted.

Little research has been carried out in Ireland on the variety of lagg types, whereas in North America there have been numerous recent studies (e.g. Howie and van Meerveld 2016; Langlois *et al*. 2015; Paradis *et al*. 2015) characterising different lagg types with a number of lagg restoration options developed for areas where it is not possible to restore the lagg in its original location (Howie and van Meerveld 2018). Recently, using twelve study sites, cutover raised bog habitats have been characterised in Ireland by Smith and Crowley (2020b). During these surveys, a small number of areas with lagg type vegetation were identified, including the one at Carrownagapppul described here. Another semi-intact lagg zone was recorded on Carrowbehy in Co. Roscommon. This site is known to support at least five bryophytes on the bryophyte *Red List* (Campbell and Lockhart 2017): *Cephalozia pleniceps*, *Sphagnum flexuosum*, *Sphagnum subsecundum*, *Sphagnum teres* and *Sphagnum warnstorfii*. In order to ensure that a range of lagg types are restored across Ireland, it is recommended that a characterisation of lagg types should be developed encompassing vegetation, geological and hydrological studies.

Understanding lagg vegetation and the factors that influence its development, maintenance and restoration will ensure that appropriate and comprehensive conservation and restoration management strategies are developed and implemented (Howie, Meerveld and Hebda, 2016). Such information has particular relevance, as recent policy measures in Ireland include commitments to rewetting grassland on organics soils (*Climate Action Plan 2019* and the recent European Innovation Partnership project FarmPEAT). Grasslands on reclaimed bog and fen peat are the prevalent land use surrounding almost all of Ireland's raised bogs, and appropriate management measures could target the re-establishment of lagg zones in key areas, thus returning bogs to a more natural functioning status within the wider countryside. For example, *The Living Bog* project identified key areas through hydrological modelling that are potentially suitable for lagg restoration on Ferbane and Raheenmore Bogs. The FarmPEAT results-based agri-environmental project is trialling incentives and management methods for farmland on peat soils at the margins of Ferbane, Raheenmore and several other raised bogs. The results of this pilot may provide appropriate mechanisms for lagg restoration, provided that their implementation is underpinned by a good understanding of Irish lag-zone ecology and hydrology.

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